IMPROVING PROCESS STABILITY IN STAMPING OPERATIONS THROUGH DESIGN OF EXPERIMENTS METHODS

by

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DECLARATION

This thesis contains no material which has been previously accepted for the award of any other degree or diploma in any university, institute or college, and to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference is made in the text.

ABSTRACT

Sheet Metal Forming particularly in the area of Stamping has been and continues to be a challenge to the field of Science & Engineering. The reason for this is the complexity of Stamping Operations owing to the inherently large number of variables inherent in the Stamping process.

The focus of this thesis was to generate a better understanding of sheet metal stamping by analysing the variables affecting the process using FE analysis and Design of Experiments. This enables one to determine which process variables (or parameters) actually influence the stamping process and by how much.

In addition to this, the important parameters were controlled in order to achieve process stability and repeatability by optimising their settings. The developed understanding has enabled production staff to operate the stamping process more efficiently and effectively using a methodical approach to production problem analysis rather than the classical haphazard approach.

Thesis Supervisor: Dr M.J. Cardew-Hall, Senior Lecturer of Engineering Department

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CONTENTS

NOMENCLATURE

σ_e = Engineering Stress
P = Applied Load
A_o = Original Cross Sectional Area
ε = Engineering Strain
l = length
l_o = original length
σ_y = Yield Stress
E = Youngs Modulus
σ_u = Ultimate Tensile Stress
σ_1, σ_2, σ_3 = Principal Stresses
τ_{max} = Maximum Shear Stress
k = Shear Yield Stress
σ_t = True Stress
A_i = Instantaneous Cross-Sectional Area
ε_t = True Strain
n = Work Hardening Index
r_w = Anisotropy
Δr = Planar Anisotropy
r_m = Normal Anisotropy
F_r = Frictional Force
η = Co-efficient of Friction
F_n = Normal Reaction Force
μ = Population Mean
N = Sample Population
σ = Population Variance
SS = Sum of Squares
DF = Degrees of Freedom
T = Grand Total of all observations
N = Total Number of Observations
T_c = Total for each Column
T_r = Total for each Row
T_g = Total for each Group
c = Number of Columns
r = Number of Rows
g = Number of Groups
n = Number of Observations
SS_c = Sum Between Columns
SS_r = Sum Between Rows
SS_g = Sum Between Groups
SS_{rg} = Row Group Interaction
SS_{cg} = Column Group Interaction

SS_{cr} = Column Row Interaction
SS_{crg} = Column Row Group Interaction
$SS_{residual}$ = SS within Columns

CHAPTER 1

INTRODUCTION

1.1 General Background

This project was unlike most Master of Engineering projects in that it was conceived at the outset as "Industry Based". This meant that the student would be required to spend a considerable period of his/her time in a shop floor environment in order to gain a fuller understanding of the sheet metal forming process (stamping), how it operates, what it involves and what it is influenced by. Thus the project was to have a rather strong industrial focus not only so that the student would be more effective due to his/her understanding, but also in order that a real problem could be solved.

This approach is not common in Master of Engineering degree Projects. The format was pursued in order to fill a perceived gap existing between research theory and practice. Whilst many of the traditional lines of research in sheet metal forming have raised the overall body of knowledge in the fundamentals of stamping operations, very little of this type of information nor approach is used by shop floor staff. The overall drive of the project was to improve the repeatability of the drawing operation of the stamping process. It is quite common, for example, to have a method of setting up the draw press at the beginning of a production run based on the ideas and opinions of one, or more, stamping personnel which in turn are based on hearsay or previous experience. This particular method may work some of the time. Yet, quite often, the method does not work with no feasible explanation as to why. Furthermore, it is quite often the case that a drawing process producing a part satisfactorily during a production run, suddenly becomes unstable and no longer produces a satisfactory part. Once again, there is no feasible explanation and attempts to rectify the problem may even make it worse since the methods used to attempt a fix are haphazard and based on personal experience. Hence the desire to introduce a level of repeatability in the process based on real process data which has been scientifically recorded.

1.2 Aims and Objectives

The specific aims of this project were:

- To develop an understanding of the process physics in the context of the Ford stamping line at Geelong.
- Derive a suitable model of the stamping line in a format suitable for process engineers to carry out DoE simulations.
- Use scientific methods to make actual improvements in press shop operations rather than the traditional "rules of thumb".
- Improve the relationship between industry and academia in order to make "industry based" projects ongoing to the benefit of both parties.

1.3 Scope

The Stamping Process is very complex and there were many avenues of investigation in which our efforts may have been channelled. Initially, it was thought appropriate to explore the following areas:

- Design of Experiments encompassing all the variables of the stamping process.
- Finite Element modelling of the process.
- Die Design.

- Characteristics of friction within stamping, particularly deep drawing.
- Instrumentation of the machinery in order to facilitate accurate measurement and recording of Process variable data.
- Investigation of the manufacture of steel and its role in the stamping process.

Due to time and system constraints, it was not possible to incorporate all of these points into the project. Thus, the focus of the project became how an improved understanding of the process could be gained by DoE methods and how this knowledge could be used to optimise the process.

It was decided to focus on a particular part which was not overly complex in a geometrical sense yet presented enough difficulties during setup and production to warrant significant effort in terms of scientific research. The part chosen was known as the Rear Floor Pan and was a structurally significant part of the chassis of the then current model Ford Falcon Sedan. Typical problems experienced prior to research included large splits in the drawn form of the part. A split is the extreme case of stretching. It is the result of the sheet metal being worked beyond the plastic range and failing. Wrinkling in some areas was also a problem however not to the extent of the above mentioned problems. A wrinkle is the buckling of the sheet metal brought about by compressive stresses which may be induced by any number of combination of forces acting within a die set. The other area of concern was excess drawing occurring in certain locations providing insufficient material for spot welding later on in manufacture in a condition known as "short flanges".

A second project was run in parallel with this project which involved the construction of a Finite Element model of the Rear Floor Pan. Simulations of this part were carried out using this model and comparisons made with the actual part produced in the Stamping Plant.

1.4 Background

Stamping of Metal was one of the first processes to come out of the industrial revolution and is hence one of the oldest. Since the time of its origins, it has not changed very much in terms of the physical methods used to achieve the end product and is a very difficult process to control. Observing the process one notices that is has a very short cycle time. It is unlike other manufacturing processes, such as turning, where even an outsider may quite easily appreciate the interference of the cutting tool with the work leading to deformation and a desired profile - a process where one may stand back and watch this process for a few minutes, see the work being rotated at high speed, seeing the tool progress slowly along the length of the work. The newcomer to the Stamping Process has no such luxury, this person sees a flat piece of metal slide into a cavity, cowers as a monstrous piece of metal rushes down on top of it, waits in anticipation as a large thump is felt and stares in awe at the piece of intricately shaped metal which comes out at the other side of the machine a second later - wondering what on earth happened.

Because stamping as a process is so difficult to understand, it has often been analysed by scientific groups as the classical black box with a series of inputs, the settings of which affect a series of outputs. A common analogy given by Keeler[61] is that of the simple bicycle lock, a series of tumblers where the correct combination of numbers causes the lock to open. The user isn't interested in the mechanics of the lock, he just puts in the right combination and the lock opens. It is almost the same in stamping, nobody really understands the mechanisms affecting the process yet fiddling around with the inputs (shut height, amount of lubrication etc) will eventually yield an acceptable series of outputs (metal properties, shape, surface finish to name a few). The difference between the simple bicycle lock and stamping is among other things a single solution. In the bicycle lock situation, there is one and only one correct sequence of numbers constituting the solution. However, in the stamping process there may be several values for one variable which are satisfactory in combination with others. The basic mechanics and physics of the process are reasonably understood. The overwhelming problem lies in the fact that most stampings are so geometrically complex that prediction of the output of the process is difficult if not intractable. However, practically one way to get the process running is to carry out experiments, measure and monitor every input and output possible and find which combination or combinations of variables work best. Thus one comes to appreciate a safe "window of operation" rather than a single setting to achieve a desirable outcome. From a production standpoint, it is better to have a "window of safe operation" rather than just the one setting, since this allows for a certain leeway or margin of error which is inevitable in the shop floor environment.

The convenient aspect of this approach is that for the moment, one is not overly concerned about why certain input variable settings yield unacceptable outputs, it is enough to obtain some sort of understanding as to which variables have a larger effect and which variables have a smaller effect on the outputs and which combinations lead to a better if not safe region of operation. It is at this stage that one develops the most "understanding".

1.5 Introduction to Press Shop Operations

The manufacture of automotive panels requires considerable amounts of force. In the Heavy Press Shop at Ford Motor Company in Geelong, the capacity of the heaviest individual press is in the range of 1250 tons. Most parts in the Heavy Press Shop are formed in a similar way. They start off in the form of a flat blank of sheet steel and proceed through a number of presses, each press performing a different operation where they emerge at the end of the line as the finished part. This part will necessarily have a combination of contours, flanges, holes and many other geometric features.

Most of the forming to obtain this finished shape is achieved during the first operation which is almost always a drawing operation hence the term - draw press. The subsequent operations usually perform minor details such as re-strike, piercing, flanging etc. Therefore the crucial operation is the first operation since most deformation is occurring here. Although the first press is colloquially known as the *draw press*, this term is not truly accurate since it is an extremely rare scenario in which pure draw is achieved. In most draw presses, a combination of stretch and draw is occurring simultaneously, this is in fact necessary to achieve plastic deformation thereby ensuring the part remains deformed. Figure1 below shows a side and front elevation of a typical draw press and an Open Back Inclined (OBI) press. As can be seen from the drawing, a large mechanical straightside press consists of the crown, four columns (supporting the crown) and the foundation. The crown houses and supports among other things, the power source (electric motor), clutch & brake and the transmission mechanism (gearbox including eccentric gears). Suspended from the eccentric gears are what is known as the pitman arms or in the case of a connection which prescribes a purely vertical motion - plungers.

A die set consists of a lower and an upper die. The piece of metal to be formed is placed on top of the lower die and the upper die is forced onto the lower die until the set is closed shut. The lower die rests on the bolster which is supported by the foundation at the bottom of the press. The upper die is connected to what is known as the ram. The ram is normally suspended above the lower die by the pitman arms. When a press is cycled, the brake is released while at the same time, the clutch is engaged. This causes power to be transmitted to the eccentric gears which forces the pitman arms and hence ram downwards. This subsequently causes the upper die to be forced down onto the lower die as previously described. As the press continues to cycle, the eccentric gears continue their rotation thus bringing the pitman arms back upward and raising the ram and upper die. At this stage, the formed part is extracted from the lower die where it proceeds to the next operation.

Depending on the part, the nature of a die set may be quite complicated. A draw die set consists generally of four parts. These being the punch, the lower die, the upper blankholder and the lower blankholder see Figure2. The punch is nested inside the upper blankholder to form a single unit forming the upper part of the die set. The motion of the punch however lags the motion of upper blankholder by a certain amount determined by the press manufacturer. This is made possible by the fact that the ram itself consists of two main parts, the inner and outer ram. The punch is connected to the inner ram whilst the upper blankholder is connected to the outer ram. When the die set is shut, the upper blankholder matches the lower blankholder identically both in dimensions and in profile. This is also true of the punch which mates with the lower die.

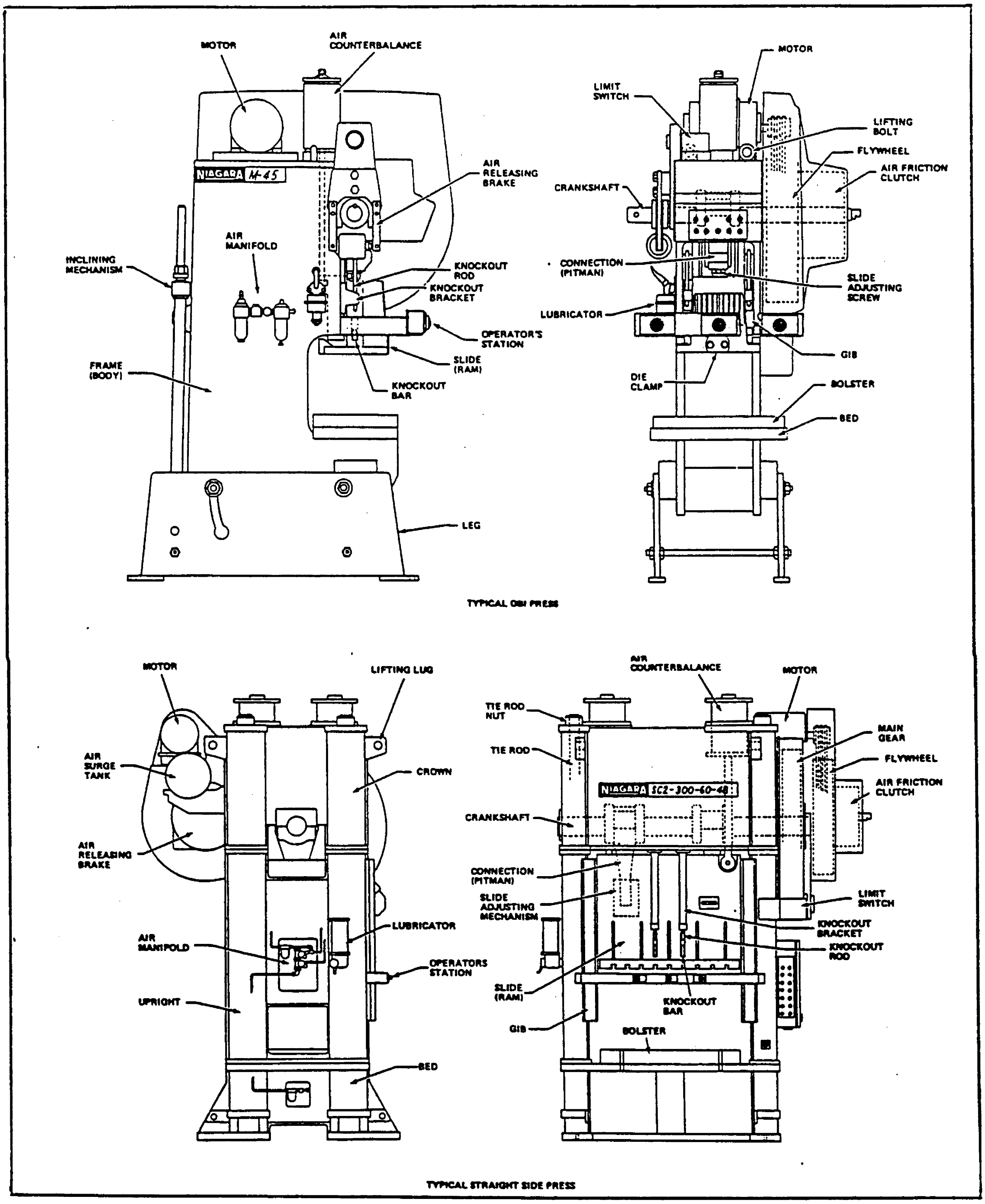


Figure1 - Typical Mechanical Presses (Sheet Metal Forming[24])

In a drawing operation, the piece of metal to be deformed is placed on top of the lower blankholder with its periphery covering most of the surface. As the press cycles, the upper blankholder is forced down by the outer ram and closes over the piece of metal (blank) applying a blankholding force. This action is closely followed by the punch which is forced downward by the inner ram and makes contact with the blank. The punch continues on its downward motion forcing the blank downwards into the recess or cavity, *drawing* the blank from between the upper and lower blankholder and forcing it to conform to the profile of the lower die and profile of the punch surface.

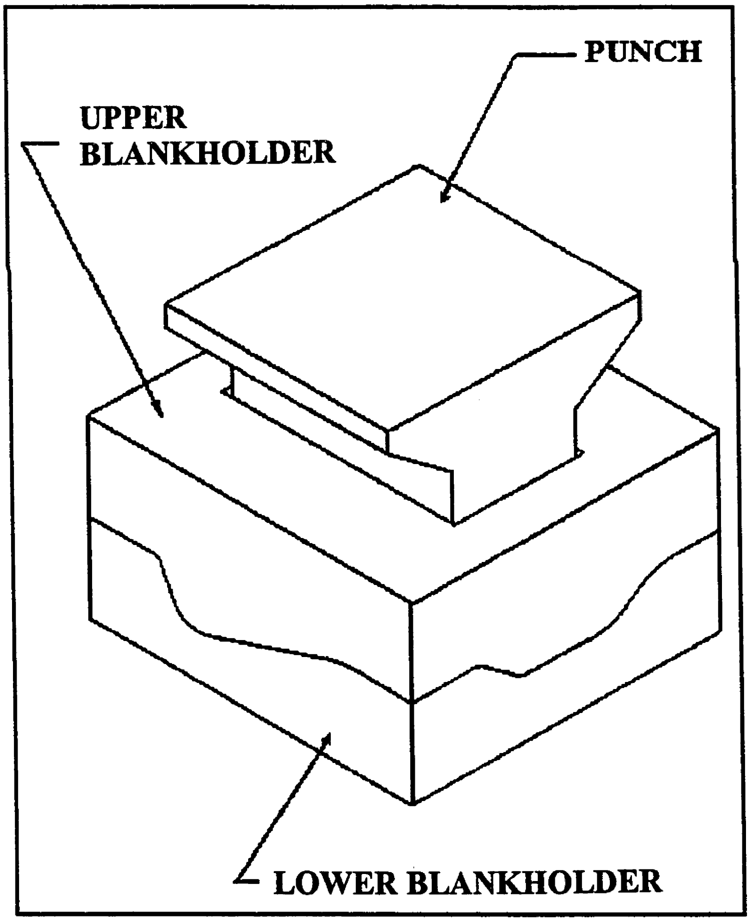


Figure2 - Draw Die Set

The eccentric gears continue to rotate acting to raise the inner ram and hence punch followed closely by the outer ram and hence the upper blankholder. The drawn part is then extracted and placed into the next operation. In a drawing operation, it is important to be able to vary the amount of clamping force required to maintain an amount of friction force between the upper and lower blankholder. There is usually an adjustment device built in as part of the connection between the pitman arms and the ram to allow for different die set sizes. This adjustment raises or lowers the ram with respect to the pitman arms. Thus as the press cycles, the ram undergoes a reciprocating motion, not unlike that of a piston in a combustion engine, where the terms of top dead centre and bottom dead centre are common and can be applied in the same manner to a press ram.

By making adjustments at the connection between the pitman arms and the press ram, the relative displacement of the press ram at bottom dead centre may be varied. This variation controls the clamping pressure developed when the upper blankholder meets the lower blankholder. This is the first of two methods which can be used to vary the blankholder force on the blank. The second method is the use of draw beads.

A draw bead acts to impede metal flow by offering resistance to the punch in the form of a raised section or profile located on the surface of either the upper or lower blankholder at locations where otherwise insufficient blankholding force is occurring. This raised section is an obstacle over which the sheet metal must bend and as such requires more force to be used to enable the metal to be drawn from between the upper and lower blankholder surfaces. In the extreme case, this bead can be formed with sharp corners in which case it totally prevents metal flow and is called a lock bead. In the latter case, deformation in the sheet metal in the area between the punch and blankholder surfaces will be almost purely stretching, see Figure3.

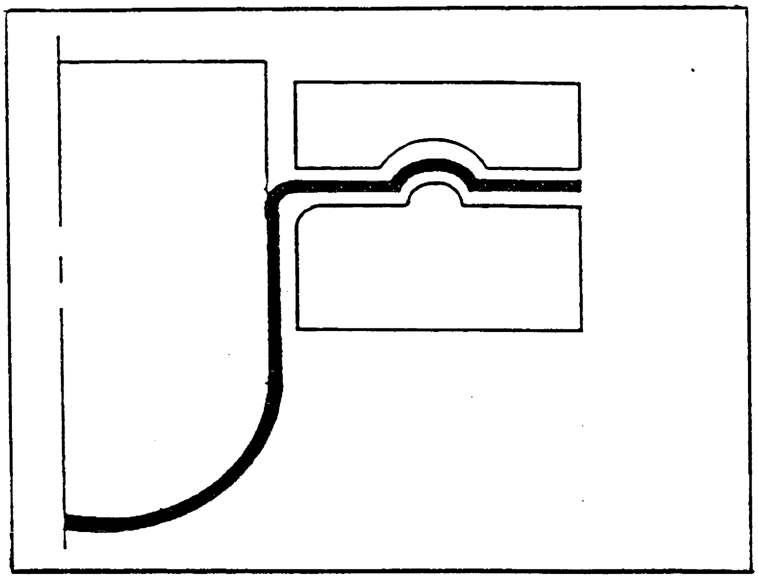


Figure3 - Draw Bead

The ability to control metal flow is essential as the profile of a part may require a lot more stretch and flow in particular areas. This is due to the particular profile of the part in question. Stretch and Draw are important because being characteristics of manufacture, they are necessary considerations of the design process. For example, a part requiring stiffness in a particular location will need to have an amount of stretch imparted to it at that location, the reason being that stretch corresponds to strain or strain hardening of the material. On the other hand, a design requirement of a particular part may require that it possess a certain height or shape (generally much larger than a geometric feature common in stretch forming). In this instance, pure draw would be required to meet these parameters.

However, pure drawing may 'result' in compressive stresses arising in the drawn blank as it deforms over the punch an die. This will result in undesirable wrinkling.

Stretching, or tensile plastic deformation of the blank is required to stop wrinkling. This tensile stress is induced in the blank by the binder force an draw beads outlined previously.

In the majority of cases, a component will need to fullfil various criteria such as strength or unique geometry and as such will require some combination of stretch and draw. The ability to form a panel satisfactorily is also determined by the way in which the press is set up. If, for example, the punch displacement is less than that specified during the design of the die, the metal will not be drawn fully into the die cavity. In the opposite situation, excessive punch or blankholder displacement can cause unnecessary thinning, undesirable form and even failure in the extreme case.

Thus one comes to appreciate the notion of input variables and output variables and the interplay between them whereby certain values for input variables cause certain values for output variables, the stamping process being the interaction between them [61]. In the case just described, the clamping force, punch force and die profile would be input variables whilst the dimensions of the finished part as well as presence of splits or wrinkles would be some output variables. It is therefore highly desirable to have the ability to measure and record both the distribution and amount of force required on both the blankholder and the punch for a particular part over a whole production run. In this way, it is possible to observe any variations occurring in force during die setting and production.

1.6 The Artisan Way

The way of the Artisan is the current method by which press shops operate and it is the Artisan upon which a Company relies in order to produce acceptable parts. A description of the methods of the Artisan is given by Keeler [60]. The skill of the Artisan is directly derived from the trial-and-error process in one of three forms. First, the long trial-and-error work style of the skilled Artisan teaches the apprentice many successful tricks of the trade which he can usually apply again should an identical set of conditions ever be encountered. One can tap this source of *how-to-do-it* information over a long time frame, such as during extended apprenticeship programs. Most of the time, however, the Artisan has no comprehension-or at worst a misunderstanding-of why a specific trick works in a specific case.

Second, the same long trial-and-error work style also can cause the Artisan to develop an instinct, a sixth sense, or a feel for which path he should attempt in a situation which closely approximates but is not identical to previous history.

The third trial-and-error situation is that attempted by the Artisan when he encounters an entirely new parameter, such as a new metal, a completely foreign part design, or a radically different forming technique. Documentation of the Artisans's response behaviour to such an environment would be interesting, but tedious and only sometimes useful [60].

When addressing common problems in sheet metal forming such as splitting or wrinkling, there are some basic tools which the Artisan and his toolmakers use. The aim is to get the metal to stretch or draw in the desired way to solve the problem being encountered. An Artisan, will quickly point out where the metal is or isn't stretching/drawing indicating where no work is being done on the metal. To rectify these problems, tool modifications may be introduced in order to induce work to be done. These tool modifications may be the addition of draw beads, shims or modification of die radii. However, adjustments are sometimes made to the press such as altering the blankholder force, changing the amount of lubricant or shifting the blank position. The supervisor and toolmakers try to interpret what is causing the problem, metal may be being gripped between the upper and lower blankholder with too much or too little force, for example. It may be the case that the sheet metal is not being worked very much at all in a particular area which would ideally require more work to be done to the metal at this location to increase the strength of the component in this location. The component may, for example, be a structural component and as such would require a higher degree of strength than a non-structural component. In this case, the die may be modified in order to grip the metal with more force in the immediate vicinity of the area in question. This causes more stretching hence, causing the area to be worked to a greater degree and increasing the overall stiffness. However, it appears that in solving these types of press shop problems, (splits, wrinkles, incorrect form etc) there is a constant trade off between splitting and wrinkling, remembering that one is the extreme opposite of the other.

For example, an oil pan component may be splitting in a corner at a reasonably generous radius. Close to this area, slight wrinkles are forming near the binder but the draw itself is unaffected and otherwise the part is acceptable. If upper blankholder displacement is reduced easing the blankholder pressure, the metal will flow more easily at the corner and the splits may disappear. However, easing the binder pressure has caused the wrinkle prone area to develop adversely causing large wrinkles and incorrect form.

This is indeed a difficult problem because solving one problem introduces another. A typical solution might be to put in an extra draw bead where the wrinkles are forming, holding the metal there and still easing the blankholder pressure. This could solve the splitting problem and the drawbead should hold the metal sufficiently to prevent adverse wrinkling. In this case, because the die is rather small in comparison to other dies found in the automotive press shop, this approach is the most suitable. Another job, however, may be much larger with the part extremities close to the edges of the ram. In this case, shimming the die in a corner where splitting may be occurring may solve the problem without having to ease the blankholder pressure which would otherwise effect other areas of the part possibly adversely. This example serves to illustrate the general work practice of the artisan. Whilst the methods used by the Artisan are usually successful, their application tends to be unstructured and non-quantitative. The Artisan generally does not know explicitly the interaction between variables on the quality of the part,he/she may have a good intuitive feel for it, but no hard data.

A more effective way to achieve a rapid solution to the problems encountered is to use structured scientific methods to assist the Artisan.

1.7 Alternative Approach

Bearing the previous statements in mind, it is necessary, in the eyes of both some academic groups and automotive companies, to apply scientific principles in practical ways. It is felt that by appreciating and understanding the variables acting within the stamping system and then further by controlling them, some satisfactory level of operation may be obtained, a level of operation which is deemed repeatable and stable.

It is proposed that the order in which problems should be tackled and the tasks which need to be addressed in order to make some sort of impact on the stamping process are as follows:

1. Develop an understanding and appreciation of Stamping as a System.
2. Focus on a particular part and identify the variables acting within the process and manufacture of that part, from the raw material to the finished product. Identify which variables are inputs, that is variables which may be changed to control the process. Identify which are output parameters, parameters by which the part quality is measured and identify input variables which are not controllable but which still have some impact on how the part is produced.
3. Determine which of the control variables appear to be the most influential and whether or not one is able to measure and record these variable settings. Implement systems to measure and record values for the variables identified.
4. Conduct a preliminary Design of Experiments (DoE) incorporating what is understood to be the most crucial variables in order to get real data and information on what really affects the stamping process and how.
5. Analyse the above recorded data and determine which variables are the most influential to the process. Focus on these and carry out another set of Design of Experiments using these variables only, working at substantially more levels than in the preliminary DoE.
6. Conduct as many DoE's as it takes to generate an amount of data to enable the determination of a safe region of operation (i.e. good variable settings). If after this time, the measurements show complete randomness

and it is not possible to determine a safe region of operation, go back and look at how the variables are being measured and try to identify variables which may have been neglected. Repeat the DoE process.

CHAPTER 2

THEORY OF DEEP DRAWING

2.1 Introduction

2.1.1 Stress, Strain & the Simple Tensile Test

Sheet metal as used in the deep drawing process undergoes an elastic/plastic deformation. For this reason, the simple tensile test can yield the properties of the material in question which can then be used for subsequent analysis. The simple tensile test is a universal method used to determine the strength deformation characteristics of a wide range of materials, especially steel. Consider a simple homogeneous thin bar of uniform cross-sectional area (Figure4) with a load applied at each end.

Engineering Stress/Nominal Stress (σ_e) is defined by the ratio of applied load (P) to the **original** cross sectional area (A_0):

$$\sigma_e = \text{Eng Stress} = \frac{P}{A_o} \quad \text{.........(1)}$$

Under these conditions, the specimen will elongate such that it now has a length greater than the original length. *Engineering Strain* (ε) is defined as the a ratio of change in length to the **original** length:

$$\varepsilon = \text{Eng Strain} = \frac{l - l_o}{l_o} \quad \text{.........(2)}$$

Now consider the tensile test and a stress vs strain graph for a typical metal (Figure5). Load is applied and the specimen is deformed at a constant rate until it fractures. As the load is applied to the specimen, it elongates in proportion to the load. The stress induced in the specimen increases linearly up until a point called the yield point. The stress at this level of deformation is called the *Yield Stress* (σ_y) shown as LYS in Figure5. This

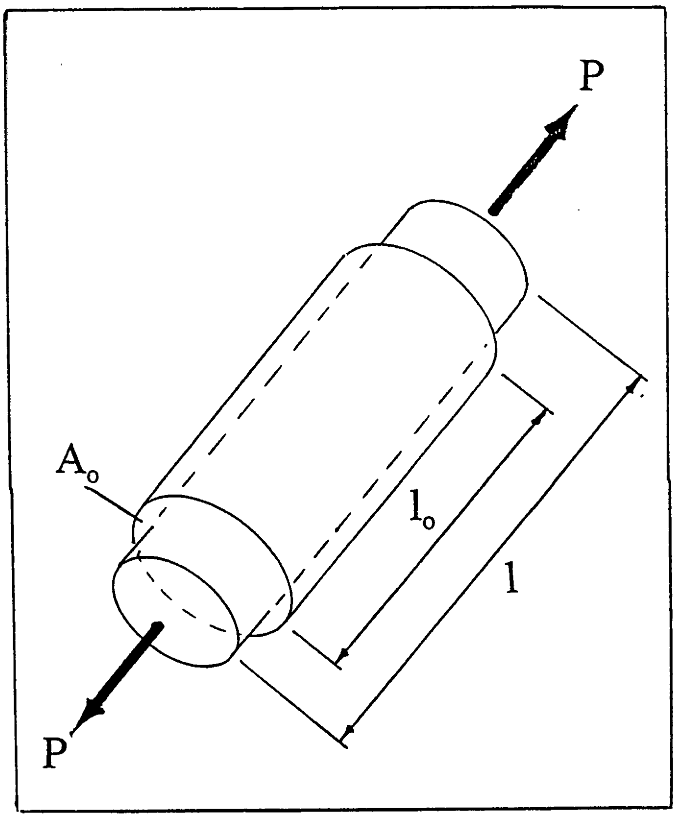


Figure4 - Simple thin bar under tension

portion of the graph is called the elastic region. Within this region, removal of the applied load will cause the specimen to return to its original length. The gradient of this graph is called the modulus of elasticity or *Youngs Modulus* and is defined by:

$$E = \text{Youngs Modulus} = \frac{\sigma}{\varepsilon} \qquad \text{...(3)}$$

This linear relationship is known as *Hooke's Law*. The portion of the graph after the yield point is called plastic region. Once the specimen is deformed past the elastic limit, on removal or relaxation of the applied, the specimen will not return to its original length. The local maxima of this graph corresponds to the *ultimate tensile strength* or *ultimate tensile stress* (σ_u) of the material. This

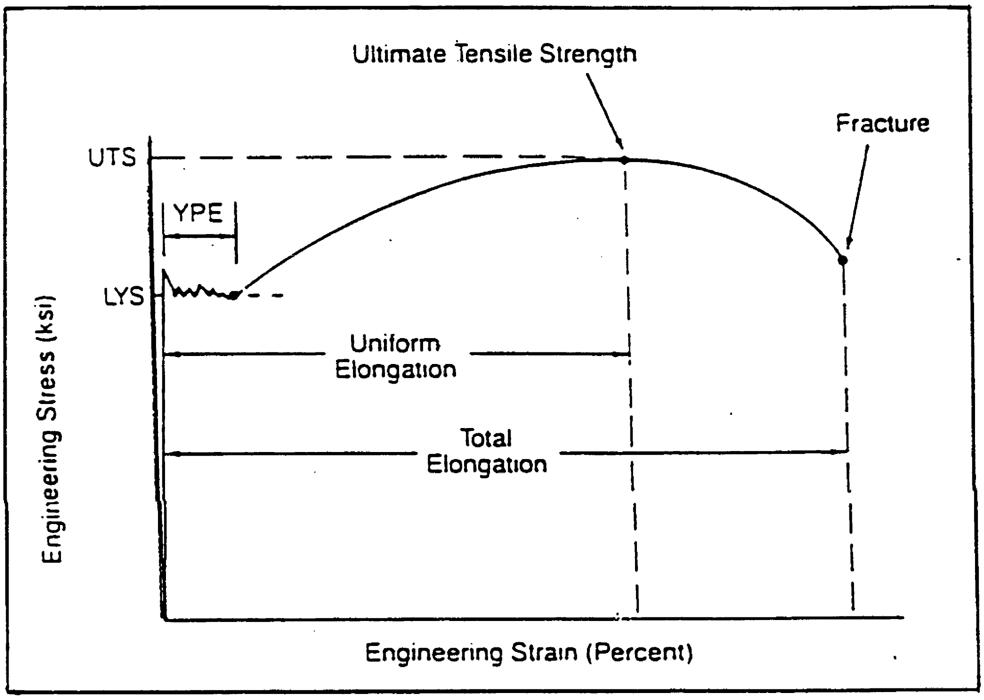


Figure5 - Stress vs Strain graph

corresponds to the maximum amount of load which may be applied to the specimen. Any further deformation will relieve the stress in the specimen and ultimately result in failure of the specimen. In practical terms, it is not advisable to deform the part past its ultimate tensile strength because one is risking failure of the work material. The amount of deformation required to reach the ultimate tensile strength is known as *Uniform Elongation*. Beyond this point, the specimen begins to neck down (Figure6) until fracture occurs and the portion of the graph between the ultimate tensile strength and fracture is known as the *Instability Region*. The total amount of deformation required to fracture the specimen is equal to the sum of the uniform elongation and the instability region elongation and is known as *Total Elongation*.

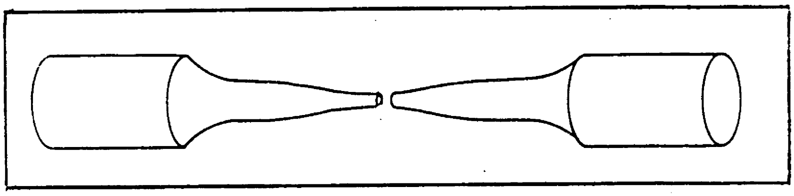


Figure6 - Specimen during necking

2.2 Plasticity

2.2.1 Yield Phenomena

Some metals do not make a smooth transition from elastic deformation into plastic deformation. Instead, they undergo what is known as *Yield Point Elongation*. Yield Point Elongation is characterised by a section of the stress strain graph which corresponds to constant load with increasing strain (see Figure5). This is caused by interstitial or substitutional impurities which cause a discrete band of metal at a stress concentration to be formed. This usually occurs at the grips of the tensile testing machine. This Yield front continues to propagate towards the center of the specimen forming bands known as Lueders bands. These bands cause defects in Sheet Metal Forming affecting the quality of finished components in terms of appearance and finish.

Lueders bands may be minimised or even eliminated using either of two processes. The first is treatment of the steel during manufacture with aluminium leading to the formation of aluminium nitride. Such steels are called aluminium-killed steels. The other process is temper rolling or flex rolling where the rolling action causes carbon and nitrogen atoms to separate from dislocations. This enables the Lueders bands to merge very quickly whereupon uniform deformation begins.

However, if sheet coil is left unused for longer than 2 to 3 months, then *Strain Ageing* in some drawing steels may occur. This means that the nitrogen is once more allowed to diffuse to dislocation sites, impeding dislocation movement. This causes the re-emergence of Lueders Bands. This may actually increase the strength of the sheet steel and can be observed in a tensile test carried out under certain conditions. If for example, straining is interrupted and sufficient time is allowed for the interstitial nitrogen atoms to seek new dislocation sites, the application of load at this point will not cause further plastic deformation rather some elastic deformation, followed by Yield Point Elongation and then plastic deformation and finally fracture.

2.2.2 Yield Criteria

The simple tensile test enables one to determine how a material will behave under loads and will reveal the general properties of the material. Figure 7C shows an element of material subject to three principal stresses σ_1, σ_2, σ_3, and it shall be taken that $\sigma_1 > \sigma_2 > \sigma_3$. Most drawing steels are tough. Toughness is defined as the amount of energy absorbed by a material as it fractures. It is indicated by the total area under the material's stress-strain curve. For a material to be tough, it must exhibit both strength and ductility. Strength, in particular Yield Strength, is simply the point at which relaxation of the applied load will not allow a material to resume its initial shape. Ductility however, is a measure of the degree of plastic deformation that has been sustained at fracture. Bearing this in mind, one is able to appreciate that the larger the strength and ductility, the more area there will be under the stress-strain graph and hence the higher the toughness.

Unfortunately, in an industrial sheet metal forming environment, the stress states induced in a simple uniaxial tensile test are rarely encountered. In most manufacturing process, the material is generally subjected to a *triaxial* stress state. In the case of sheet metal forming, such as the wall of the classical cup in Figure7, this reduces to $\sigma_3 = 0$.

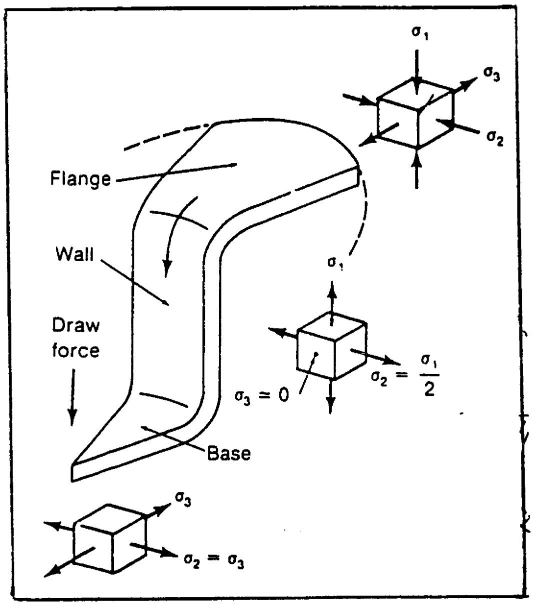


Figure7 - Stress States in a cup draw

The fact that a triaxial and not uniaxial stress state exists in most manufacturing processes has lead to the postulation of several of several theories regarding the yield criteria of metals that relate uniaxial test results to bi & triaxial stress cases [54].

The maximum shear stress criterion or *Tresca Yield Criterion* states that yielding will occur when the *maximum shear stress* (τ_{max}) within an element is equal to or exceeds some critical value. For yielding to occur:

$$\tau_{max} > k \qquad (4)$$

where k = shear yield stress. A convenient method for calculating the stresses on an element is by plotting a *Mohrs Circle*. A Mohrs circle represents all possible states of normal and shear stresses on any plane through a stressed point in a material (see fig7b). It is governed by the equation of a circle of radius R defined below:

$$R = [0.25(\sigma_x - \sigma_y)^2 + \tau_{xy}^2]^{0.5} \quad \text{.........(5)}$$

and whose centre has the co-ordinates

$$[0.25(\sigma_x + \sigma_y),0]$$

The Mohrs circle for typical stress states are shown in Figure8. Here, one can easily see how combinations of stress states lead to the

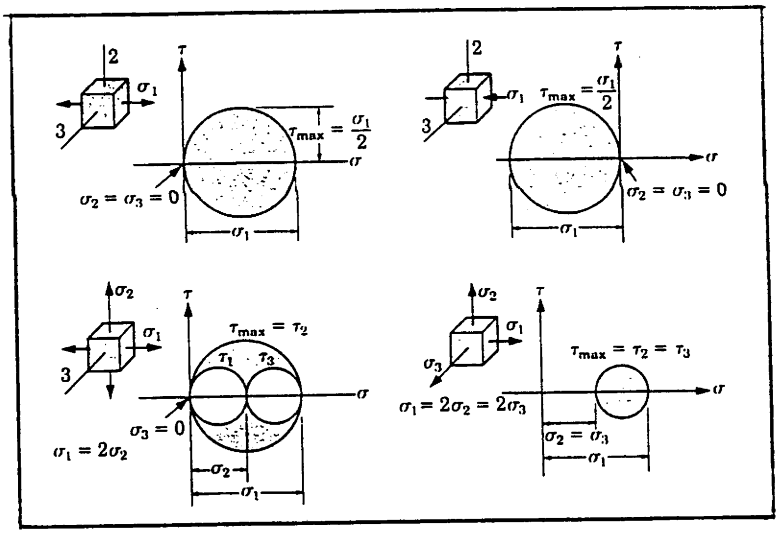


Figure8 - Mohrs circle for typical stress states (Mechanics of Engineering Materials[7])

construction of a circle. If the radius of this circle exceeds the maximum shear stress, then yield will occur. From this we conclude that the maximum and minimum normal stresses produce the largest circle and therefore the largest shear stress. For the simple tensile test,

$$k = \frac{\sigma_y}{2} \qquad (6)$$

where σ_y = Uniaxial Yield Stress

The Tresca yield criterion is therefore written as:

$$\sigma_{max} - \sigma_{min} = Y = 2k \qquad (7)$$

Another common yield criterion is the *Von Mises Yield Criterion* or distortion-energy criterion. This criterion states that yielding occurs when the relationship between the principal applied stresses and the uniaxial yield stress (σ_y) of the material obeys the following equation:

$$(\sigma_1-\sigma_2)^2 + (\sigma_2-\sigma_3)^2 + (\sigma_3-\sigma_1)^2 = 2Y^2 \qquad (8)$$

The difference between the two criterion are that in the Tresca criterion, the assumption made is that yielding is dependant on the maximum shear stress in the material reaching a critical value. The Von Mises criteria on the other hand proposes that the total elastic strain energy stored in an element of material could be considered as consisting of energy stored due to a change in volume and energy stored due to change in shape, in other words, distortion or shear. In both criterion, the left hand side of the equation represents the applied stresses whilst the right hand side represents the material properties.

Important assumptions are made in both of these criterion. It is assumed that the materials in question are homogeneous, continuous and isotropic.

2.2.3 Work Hardening Index

As a metal deforms plastically, it tends to strengthen and the load required for further deformation increases, this amount of strengthening is called work hardening. In section 2.3.1, a definition of engineering stress and strain were given. However, the *true stress* (σ_t) induced in a tensile test specimen is defined as:

$$\sigma_t = \frac{P}{A_i} \quad \text{(9)}$$

where A_i is the instantaneous cross-sectional area of the specimen supporting the load, whilst *true strain* (ε_t) is defined as:

$$\varepsilon = \int \frac{dl}{l} = \ln(\frac{l}{l_o}) \quad \text{(10)}$$

A log-log plot of true stress vs true strain for a typical metal would not take the form of the previous stress vs strain graph. Instead it would follow a straight line with a gradient n as shown in Figure9. This shape may be approximated by the following equation which is also the curve of the plastic deformation region:

$$\sigma_t = K\varepsilon^n \quad \text{(11)}$$

and may be re-written as:

$$\log \sigma_t = \log K + n \log\varepsilon_t \quad \text{(12)}$$

where σ_t = true stress, ε = true strain and K = constant.

This gradient is also known as the *work hardening index*. In a practical sense, the n-value gives an indication of the materials ability to re-distribute deformation loads

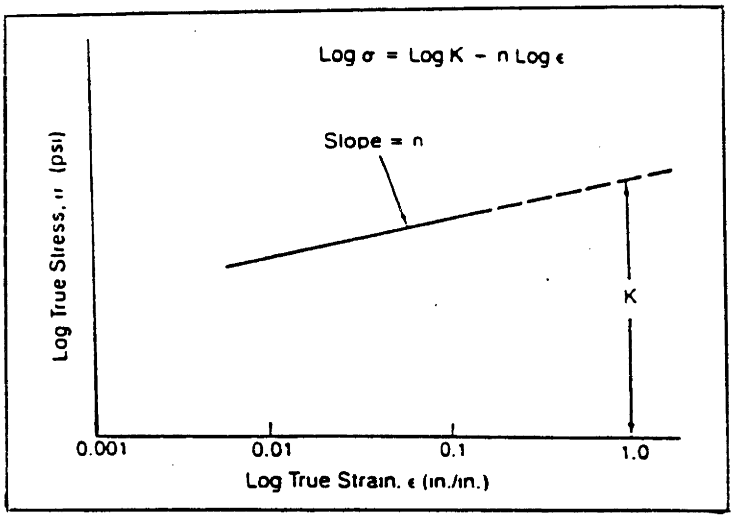


Figure9 - Log True Stress vs Log True Strain

evenly, making the process more stable. Sheet Steel with a higher n-value will stop deforming in critical locations sooner compared with lower n-value steels, forcing other areas to deform more quickly than they otherwise would. The net effect is to cause the deformation-front to move through the steel sheet more rapidly achieving a more even deformation throughout the sheet. For this reason, steels with higher n-values are sought for stretch forming.

The n value is related to the yield strength of metals, it decreases as the yield strength increases. The effect of higher n values is to enable a more uniform strain distribution which leads to reduced peak strain levels and hence less chance of failure.

2.2.4 Anisotropy

Anisotropy or r-value as it is commonly known is an indication of the directionality properties of sheet steel. Sheet steel exhibits directionality properties due to the way it is manufactured. During Manufacture, the rolling action causes the grains in sheet steel to align themselves in certain ways causing the steel to posses different properties in different directions. Anisotropy may be defined as the ratio of width strain ε_w to thickness strain ε_t of a tensile test specimen:

$$r_w = \frac{\varepsilon_w}{\varepsilon_t} \qquad (13)$$

However, there are several methods of defining anisotropy. Planar anisotropy is defined as:

$$\Delta r = \frac{r_o + r_{90} - 2r_{45}}{2} \qquad (14)$$

Normal anisotropy is defined as:

$$r_m = \frac{r_o + 2r_{45} + r_{90}}{4} \qquad (15)$$

where r_0 is defined as the anisotropy in the direction of rolling, r_{45} is the anisotropy at 45 degrees to the direction of rolling and r_{90} is the anisotropy perpendicular to the direction of rolling.

(see Figure10)

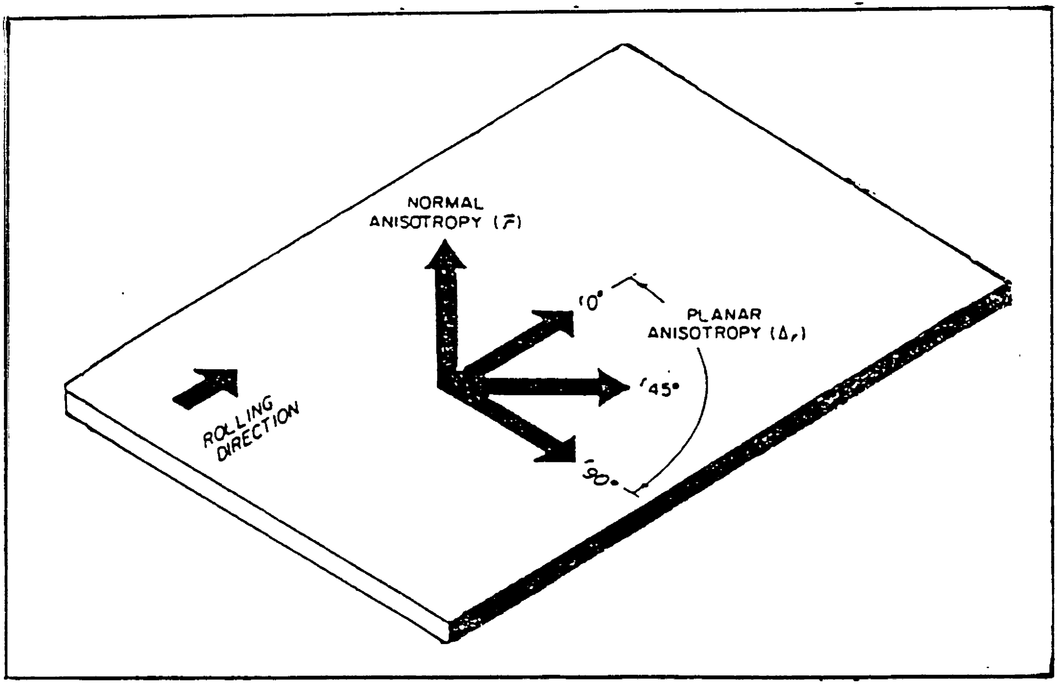


Figure10 - Classification of Anisotropy

The condition of Planar Anisotropy is undesirable in the drawing of cups as it leads to a condition known as earing, where the top lip of the cup will be undulated and non-uniform (see Figure11). Normal Anisotropy is important for deep drawing operations as it gives an indication of the materials resistance to thinning. Thus deep drawing steels commonly have a high r-value (1.2-1.4) to enable deep draws with less chance of failure. Drawing, in particular deep drawing, is sensitive to anisotropy. Drawing steels are especially manufactured to have a higher r-value than ordinary steels. This allows the material to stretch and plastically deform in the plane of the sheet and so assist in the formation of deeply drawn components.

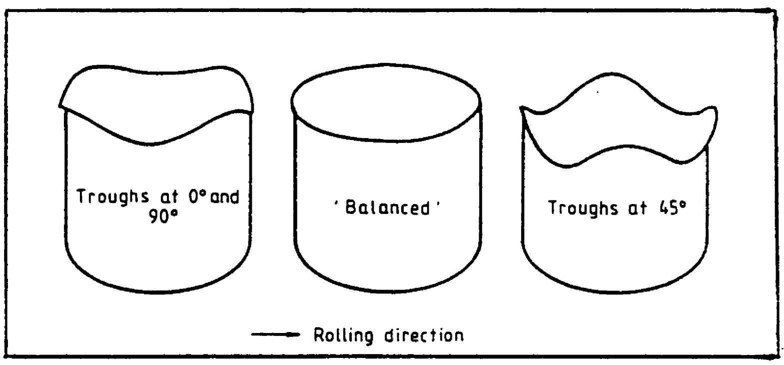


Figure11 - Earing of Cups

2.3 Friction

Friction is very important in Deep Drawing of Sheet Steel. It has a large effect on how sheet metal is restrained within a die and to what extent it is permitted to deform. If there is too much frictional force generated within a die set, excess tensile forces will be generated in the sheet and tearing may take place. On the other hand, too little frictional force being generated could allow compressive forces to be generated in the sheet which could lead to wrinkling.

2.3.1 Basic Concepts

The basic concept of friction is demonstrated by considering a mass resting on a horizontal plane. The mass will exert a force on the plane and the plane will exert an equal and opposite force on the mass F_n. A tangential force F_t may be applied to cause the mass to move. The amount of tangential force required to cause the mass to move is generally considered to be the friction force and is a function of the mass-plane system. This may also be quantified by Coulombs law:

$$F_r = \eta . F_n \qquad (16)$$

where η is defined as the co-efficient of friction. The frictional force F_r is said to be equal to the product of the co-efficient of friction and the normal reaction force of the plane on the mass [141].

2.3.2 Variables Affecting Friction

The Parameters which affect the frictional force in sheet metal forming are:

1 - Contact Pressure

This is demonstrated by the above example

2 - Sliding Speed

Experiments show that *dynamic friction*, that is the frictional force which must be overcome once the mass is in motion is smaller than *static friction*, the frictional force required to initiate motion.

3 - Surface Roughness

The shape and density of surface asperities affect friction regardless as to whether the surface is wet or dry.

4 - Lubrication and Debris

Lubrication has a very big effect on the frictional force. Type, distribution and temperature sensitivity are important. Distribution may be affected by forming pressure and sliding speed.

5 - Temperature

The local temperature at contact points on the binder surface and in the lubricant is dependant upon plastic work dissipation and thermal conductivity.

6 - Concurrent Deformation

This is important in sheet metal forming because the metal is undergoing plastic deformation. Plastic deformation changes the surface texture of the work material, changing the roughness and opening up new surfaces by dislocation slip. All of the latter are themselves very influential on the level of friction force.

2.3.3 Role of Lubricants

The role of lubricant in Sheet Metal Forming is primarily to reduce the frictional forces acting within a die. However, there are several other advantages with using lubricant. The first is that because there is less friction, there is less rubbing of the surfaces. It is this rubbing of surfaces in the die which causes the die to wear. Thus the use of lubricant aids in reducing the amount of wear which the dies receive. Secondly, the rubbing of die surfaces can lead to surface defects known as galling and scoring. These defects affect both the part and the die surface. The use of lubricant reduces both of these. The rubbing between the die surfaces can lead to a build up of heat which adversely affects the die surface. Lastly, the use of lubricant acts as a coating on the dies and prevents the oxidation of the die surface.

The type of lubricants used are dependant upon the work surface. In sheet metal forming for example, the die surface is tool steel or stainless steel. For these types of surfaces, oil based solutions of fatty oils, waxes, polymers and pigmented soaps are applicable [24].

Temperature can affect the lubricant by altering its properties. An increase in temperature above room temperature can cause the lubricant to be less effective, increasing the co-efficient of friction compared with no temperature change. Therefore, increases in temperature above room temperature have a negative effect on the lubricant and hence a negative effect on the process.

2.4 Limiting Draw Ratio

The limiting draw ratio or LDR is a common term in sheet metal forming which gives an indication of a metals ability to sustain deformation in a cup drawing operation. It is defined as the ratio of the largest blank-to-cup diameter that can be drawn successfully and governed by the following equation:

$$\mathrm{LDR} = \frac{db}{dp} \qquad (17)$$

where db is equal to the diameter of the blank whilst dp is equal to the diameter of the punch.

CHAPTER 3

PREVIEW OF CURRENT AREAS OF RESEARCH

3.1 FE Analysis

A common tool for the investigation of Sheet Metal Forming is the use of the Finite Element Method. Using this technique, the continuum or object to be modelled is divided into a *finite* number of *elements* whose behaviour is specified by a finite number of parameters. The solution of this complete system as an assembly of its elements follows precisely the same rules as those applicable to standard discrete problems. Most mathematical procedures of approximation fall into this category [127]. FE methods are varied in the assumptions made and the problem at hand. Chou, Pan and Tang [17] for example have presented a model using a stress resultant constitutive law where the effect of thickness reduction due to large plastic deformation is considered. This is used in conjunction with the principle of virtual work to derive a finite element formulation in terms of stress resultants and their work-conjugate generalised strain rates. Alternatively, Yang, Song and Yoo [131] proposed an adaptive bi-section refinement for rigid-plastic finite element analysis. They proposed that any required order of surface conformity and mesh refinement could be achieved be employing refinement according to the suggested criterion. In this case, the suggested criterion was based on the thickness-modified curvature of a general curved sheet surface.

Apart from this there has been much work using the Finite Element Method using established Codes. Ferran, Barros, Pasquale and Yamashita [33] for example analysed the simulation of the forming process of several stages of a car wheel disk with the inverse 3D Finite Element Code SIMEX. Several numerical results were predicted along with the thickness of the part which was compared with experimental results using hot rolled steel sheets with different properties and thickness. Rojek, Jovicevic and Onate [101] however used the in-house explicit dynamic Code STAMPACK in order to analyse a number of practical problems such as the stamping of a kitchen sink, hydraulic forming of an aeronautical part and stamping of a food can. Their results showed a good comparison with the actual part made.

3.2 Circle Grid Analysis

In addition to this, attempts have been made to improve Press Shop operations using Circle Grid Analysis in conjunction with the Forming Limit Diagram [3],[14],[59],[61],[66]. This is a useful tool used in Sheet Metal Forming enabling one to determine how close to failure a particular part is approaching during a given forming operation based upon the measurement of strain. The method involves electrochemically etching a series of circles in a square grid pattern on a blank in the area of interest. A part is then produced using this blank. The etched area of interest now contains a series of ellipses within a distorted grid. The purpose of the circles-cum-ellipses is to determine how much strain has taken place whilst the purpose of the grid is to determine what the direction of the metal flow is.

A line is drawn through the section of panel of interest and the amount of strain for each ellipse is determined by measuring the major and minor axis using a transparent flexible ruler called a mylar tape. Thus for each deformed circle on the chosen line, there will be two separate measurements, the major stretch and the minor stretch. This data is plotted on what is known as a *forming limit diagrams*. A forming limit diagram is shown in Figure12. The shape of the forming limit line is the same for all metals however its position on the major axis is different for different metals. The point where the forming

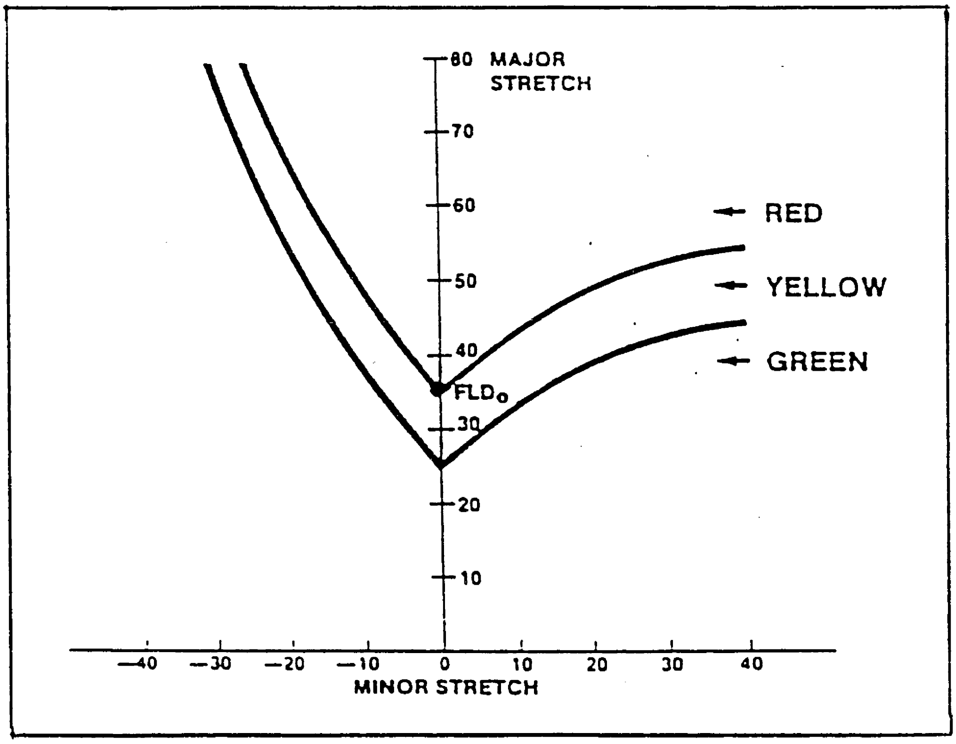


Figure12 - Forming Limit Diagram

limit line intersects with the major axis is called the FLD_o. FLD_o for metals is a function of the material thickness (t) and work hardening exponent (n-value). It is defined by the following function:

$$FLD_o = (23.2 + 14.17t).\frac{n}{0.21} \quad \text{.......(18)}$$

A forming limit diagram is often represented with two forming limit lines. The lower line intersects the major axis at FLD_o whilst the next one is generally 20% higher on the axis. Thus the forming limit diagram is now divided into three zones. The lowest zone is termed the "green" or safe zone, the middle zone the "yellow" or marginal zone and the uppermost zone, the "red" or forbidden zone. The data gathered for each successive circle is plotted on the forming limit diagram and the "dots joined".

One is thus able to see where on the forming limit diagram one is currently operating and how close one is to the marginal or forbidden zone. The forming limit diagram also gives one an indication of which direction to move in if one is operating in the marginal zone. This direction will correspond to some combination of major and minor stretch which in turn will correspond to a new direction of flow of metal which would be achieved using conventional methods (drawbeads, die modification).
Keeler [59] describes the construction and use of FLD's in order to determine what the state of the metal is currently in. Using the FLD, one is able to determine whether there is a tendency to wrinkle or split depending on the location on the FLD. This has been used by Kolodziejski [66] where he outlines a method to design out surface defects in stampings using grid straining in conjunction with FLD's. Lee [69] describes a very powerful method of analysing the grided and deformed panel using optical methods combined with computer software in the analysis. It was traditionally the case that strain was measured manually using a transparent strip commonly known as a Mylar Tape. Lee however describes a much simpler and more powerful method whereby two photos of the deformed panel are taken at different angles using a digital camera. The photos are then analysed with computer software which then generates a 3D image of the deformed part showing the levels of strain over the whole part.

3.3 Analytical Modelling

Besides the above methods, attempts have been made to model the Sheet Metal forming process using analytical methods and mathematical equations only. Mamalis, Karafillis and Vaxevanidis for example used a theoretical model to predict the limit strains and the forming limit diagrams of thin sheets subjected to biaxial stretching. Their model correlated surface integrity changes resulting from mechanical processing; either low-speed directional rolling or stochastic ball-drop forming and thermal stochastic electro-discharge machining [76].

Perotti and Iuliano on the other hand calculated average powers and forces in four-sided-piece deep-drawing based on the Upper Boundary Element Theorem (U.B.E.T). This technique pre-supposes constancy of volume and the choice of a kinetically admissible velocity distribution that meets the boundary conditions set by the tools. As deep-drawing proceeds, the distribution of the material flow may be determined. This enables the calculation of strain rates and finally the power of deformation [94].

A totally different approach was taken by Jun, Lee and Yoo. They analysed cup drawing using total strain energy theory assuming that the thickness of the sheet remained constant during drawing. This enabled them to obtain the load-stroke curve and a relationship which can predict limiting drawing ratio [53].

3.4 Experimental Approaches

Although unique in its own right, this project was by no means the first to adopt a pragmatic hands on approach to solving sheet metal forming problems. Keeler [60],[61] and [62] has demonstrated on many occasions the need to understand Stamping Operations, a very complex manufacturing environment, as a Black Box system such that one is in a better position to solve problems in a systematic and logical manner. He along with others [66] have demonstrated how Circle Grid Analysis in conjunction with the use of Forming Limit Diagrams can be successfully used to counter many difficult forming problems. Keeler also emphasises the need to obtain good quantitative data on the stamping process. This is demonstrated by the fact that the correct values of critical forming characteristics required to solve the many problems are known, yet the exact magnitude of these values is not. For example, it is possible to say that a higher r-value will improve the drawability of a steel, yet the exact increase in r corresponding to better drawability is not known. Therefore, systems predicting sheet metal formability are only as good as the data being fed into the systems [58] and it is Design of Experiments which will target the type of problems mentioned above more effectively.

Design of Experiments techniques have been successfully used in an industrial environment to tackle real problems. This inevitably involves reducing variability in a process to ensure that the inputs do not vary, or if they do, to try to minimise the range of variation [90]. It is also necessary to understand the nature of the variation such that variability which cannot be avoided can at least be compensated for in a logical manner.

CHAPTER 4

PROCESS VARIABLES

4.1 Introduction

There have been many variables identified which all have some control over sheet metal forming. The following list shows the variables which may effect the stamping of sheet metal. This list is rather general and would apply to most press shops around the world - at least where automobile parts are being made.

This doesn't however take into account other variables which may be characteristics of a particular part. For example, the draw die of a bodyside may incorporate nitrogen cylinders, balance blocks and springs to aid in restricting metal flow and thus enable a split and wrinkle free part to be produced. Nitrogen cylinder pressure and spring stiffness is not generally included in a list of press shop variables yet for the production staff, a shift in this type of variable will no doubt affect the part quality and is therefore very important and must be considered when analysing this die set.

Therefore, one may appreciate the subtle complexities of press operations where it is beneficial to look at the press shop as a system and try to incorporate all variables in an attempt to stabilise the system, however, one cannot be allowed to forget that there will usually be more variables and points to take into consideration when trying to improve the quality of a particular part and the amount of 'hidden variables' will depend upon the complexity of the part - confirming the common belief that "each job must be judged on it's own merits"

4.2 Input Variables

The input variables identified below were those observed during an in plant study, many of which were characterised by Siekirk[111]:

1. *Shut Height* - The vertical distance between the bottom of the lower half of a die to the top of the top half of a die when the press ram is at bottom dead centre. With respect to the blankholder, it affects how much force is being applied to the blankholder. The lower the shut height, the more the blank is being compressed between the two die halves. This means that the metal will not flow as easily either eliminating wrinkles, introducing splits or both or neither. For many parts, it is the primary method of adjusting the amount of frictional clamping force induced by the blankholder. With regard to the punch, the shut height will affect the amount of deformation which the blank will undergo. A shut height which is too high for example could lead to insufficient form/deformation whilst a shut height which is too low could cause the metal to thin unnecessarily, the extreme case being splits.

2. *Corner Pressure* - Corner Pressure is a convenient way of applying more or less force to the corners of the part. Corner pressure control is really part of the overload protection system of large mechanical presses. Force is not transmitted directly to the ram of a press through a mechanical linkage as one might imagine. Instead, it is transferred through a narrow interface of oil in a chamber under pressure. The reason for this is that in the absence of such a system, an obstruction in the die cavity

would prevent the ram from reaching bottom dead centre inducing much larger forces in the press structure and crown then would otherwise be experienced in a normal cycle.

The momentum of a press mechanism is such that these large forces induced would be transferred not only to the die but also upward and throughout the whole press. This could lead to bent or broken cranks and other vital pieces of machinery. In an attempt to counter this scenario, force is transferred, as previously, stated through a reservoir of oil. Should the oil pressure in this reservoir exceed some set limit, then all of the oil in the reservoirs of each point of suspension will dump into a common tank giving a clearance of approximately an eighth of an inch. It is possible during normal press operation to vary the pressure of oil in each reservoir.

This will affect how much force is applied at the point of suspension in question. Therefore, one may affect the amount of frictional clamping force acting at the blankholder at a particular corner though not to the same degree as with shut height. During on plant experimentation, for a 700 ton blankholder, it was possible to vary the force from between 350 tons to 800 tons (according to the specifications).

3.Blank Location - The blank location is essentially self explanatory. It is simply where the blank is positioned with respect to some fixed reference point on the die surface. The effect of blank location can be quite interesting. The primary effect, which cannot be observed, is the effect on the flow of metal and the secondary effect which can be observed is the final length of flanges which are a concern in assembly. A blank which has been incorrectly located can cause insufficient amount of metal at a particular location. If this location happens to be where the part is welded to another part in later assembly operations, then this insufficient amount of metal will mean that there is not enough metal to create a sufficient join.

4.Blank Geometry - This variable too, should be self explanatory. There generally is an optimum blank size. A blank which is too large may cause wrinkling or may simply be a waste of metal. On the other hand, a blank which is too small will be a constant source of trouble to toolmakers because they will be continually having to make adjustments to the press and die in order to get the positioning and other variables just right in order to get a part with sufficient form.

5.Draw Speed - This refers to the speed of the Ram as the Press cycles. It is achieved by varying the current in the magnetic clutch and brake mechanism. This will effect the rate of deformation. This variable effects the punch much more than the blankholder.

6.Lubrication - The amount of lubrication applied to the blank will greatly effect the nature of the ensuing draw. Some parts are very critical, involving complicated form and/or high rates of deformation. In these cases, experience has shown that it is almost impossible to run these parts without lubrication. In the stamping plant at Ford Geelong, there are three general methods of applying lubricant to a panel. The first is a roller coater which consists basically of two contra-rotating rolls which have lubricant applied to them, the panel is forced in-between these rolls and thus has a film of lubricant applied. The second method is by using spray units. This set-up consists basically of 4 or less spray guns located generally on the four corners of a die. These are focused onto difficult areas and spray automatically as a press cycles. This has the advantage of considerable savings in lubricant.

The last set-up is a blankwasher which washes the blanks using brush rolls and squeegee rolls and applies a film of lubricant similar to a roller coater in the last set of rolls. Lubricant is the most effective way of controlling friction. It is also one of the most difficult variables to control.

7.*Blank Thickness* - Blank thickness will effect the force needed to form a blank, final part strength and resistance to deformation. Blank thickness will also effect tool design. This is because a thicker blank will require a larger clearance in between the die halves, it will also not bend over as small a radius as a thinner blank and since it requires more work to deform may also require more generous radii within the die. Generally speaking, effort is always being directed into reducing blank thickness in order to save weight and manufacturing costs.

8.*Mechanical Properties of Work Material* - There are approximately seven different characteristics which are used to describe the mechanical properties of the work material. These characteristics include yield strength, tensile strength, elongation, hardness, uniform elongation, anisotropy and the work hardening index. Yield strength and tensile strength will effect the forming loads whilst elongation, anisotropy, hardness and work hardening index will effect the formability (drawability, stretchability). It is desired to make the stamping process robust enough such that inherent variability in sheet steel has no real effect on sheet metal formability.

9. *Coating of Work Material* - Most steel is delivered to the Stamping Plant with a coating of oil usually called mill oil. This is an anti-corrosion measure while steel coils are in storage however the technology of these oils has progressed to the stage where the oil has qualities enabling it to be used as a drawing compound or lubricant. There are cases where the viscosity is insufficient to enable it to be used as such. In this case, lubricant is applied directly over it as described in section 2.3.3. This has proved to be satisfactory although it might be interesting to see the effects of the interaction between mill oil and lubricant. Other types of coatings are applied to sheet steel before it arrives in a stamping plant as anti-corrosion agents for the finished product. Common coatings include zinc phophatization plus anaphoresis, iron phosphatization plus cataphoresis and zinc phophatization plus cataphoresis. Zinc phosphatization plus cataphoresis is generally better than iron phosphatization plus cataphoresis and zinc phosphatization plus naphoresis. Formability is generally not affected however in some cases, a build up of zinc deposits

on a punch may cause defects particularly on skin finish panels. In addition to this, lubricants are still required [19],[30] and [62].

10. *Die Geometry* - Die geometry is an extremely important variable as the design of a set of dies will determine how the metal flows within the die cavity. In plant observation has shown how blankholding force, punch force etc are affected by varying die geometries. Parts requiring a deeper draw with more complex form usually require a larger forming load. The effects of radii have also been well documented. Research has also shown how radii can have an important effect on the flow of metal easily causing restrictions and splitting if they are too small [22],[53],[62],[69] and [122].

11. *Die Temperature* - The temperature of the die will effect the viscosity of the lubricant being used. In these applications, one generally finds a film of constant thickness which is affected by the temperature of the surfaces it is in contact with. A set of dies will start at room temperature and as the press is cycled a number of times, it will begin to heat up due to the friction between the die halves and the blank. Thus the nature of the lubricant at certain locations in the die will change from die set to early in production. The problem should not last long as the temperature will reach some threshold and not increase. At this point the lubricant will become stable. Problems arise however when there is a change of shift for example and the press and dies are left to stand. They will subsequently cool and the lubricants viscosity will once more approach a value close to what it was prior to startup.

12. Use of draw and lock beads - Draw beads and lock beads are tools used in die design to assists in controlling the flow of metal within a die cavity. A difficult panel shape may be impossible to form using only a punch and blankholder. No matter how skilled the designer may be, there are always cases where beads may be necessary.

13. Tonnage - This variable is often a source of conjecture particularly between academic and shop floor groups. The realities are that in the shop floor environment, although the force offered to the die may be adjusted by various means, tonnage is something which is measured as an output and is therefore classified as such by stamping personnel. On the other hand, from an analysis point of view, tonnage is basically the amount of force required to form a part, the FE model developed as a parallel project ran in such a way that either the amount of force to form a part is specified and the resulting displacements are analysed or vice versa. For this reason, tonnage is often classified as an input in academic circles.

4.3 Static Variables

1. Counter-Balance Pressure - Although a contradiction in terms, static variables refers to an entity which can be adjusted but shouldn't be for the sake of trying to obtain a better part. In this case, counter balance pressure is a variable which itself varies as a press cycles. Counter balance cylinders are installed in either the columns or the crown of a press. They act to actually resist the motion of the press ram in order to make the motion of the ram smooth, reducing vibrations and wear of the press crown mechanism. Counter balance pressure can be adjusted but room for adjustment is to accommodate different sized dies. A larger die for example will require a higher counterbalance pressure.

4.4 Output Variables

1.Strain distribution of Part - Strain distribution of the part is basically the amount of deformation the part has undergone from blank to finished part in all three dimensions. In multistage stamping operations, the major plastic deformation and drawing occurs in the first drawing operation. It is important that excessive plastic strain is not induced at this operation as it restricts the plastic deformation that can be done at later stages.

This is not the only concern regarding strain distribution. Much emphasis is placed on the magnitude of strain and not the distribution of strain. CGA (Circle Grid Analysis) is fully applicable for single step forming operations, yet for progressive forming operations, it fails to take into account the actual strain path. This will cause incorrect strain readings to be read using CGA [112]. In plant observation has shown that most CGA is carried out only after the first drawing operation, in this case the readings given by CGA will be correct, however, one cannot assume that CGA readings lying well within the safety zone of an FLD after the first operation will mean that the part is not at risk of failure. The subsequent forming operations may well cause significant deformation not indicated by a CGA check after the first operation only. In fact problems of this nature have been documented.

Kolodziejski [66] has shown how subsequent forming operations such as trimming, notching and piercing may release residual stresses altering the existing strain distribution which may result in surface defects known as "highs and lows". These are deflections on the surface of the panel with a small amplitude (0.1 to 0.5 mm) but with a relatively large wavelength (over 50 mm). These defects occur frequently on the surface of large panels of small curvature and especially near strongly deformed regions. Therefore, the distribution and not only the magnitude of strain should be engineered into the design of the dies. In plant observation has shown that the running of skin finish panels requires constant modification to the dies when setting the job in order to reduce the number of such defects to an acceptable level.

2.*Part Geometry* - The final formed part has geometric tolerances in which the part must lie. Dimensional inspection to ensure tolerances are achieved is normally carried out at the end of a multi-stage line of forming operations. Ideally one would want to carry out a dimensional check after each operation, though in practice, this does not occur. Therefore, it is usual to make a special device to check geometries after the drawing operation for parts which are consistently troublesome.

3.*Major Defects* - These are a result of an excess in part deformation. The work material will undergo a certain amount of compression before it deforms plastically and begins to wrinkle. The extreme opposite of this condition is failure of the work material which is usually characterised by splitting.

Splitting occurs when the work material is deformed beyond its plastic limit resulting in fracture. Other major defects may be incorrect form (not as severe as wrinkling but gross distortion) and surface blemishes (highs and lows, see section 4.4 no.1).

4.Post Work Material Properties - Post work material properties are the properties of the part after it is produced. There must be a substantial amount of cold work imparted to the metal to give it sufficient strength and stiffness. This could be measured by taking samples from a finished part, however in plant observation has shown that this is rarely carried out.

The number of variables identified is large. To monitor and experiment with the effect of all the variables was beyond the scope of this project. The practical nature of the project procluded access to presses for extensive experimentation to eliminate certain variables. This was substituted with shop floor observation to isolate variables as described above. In order to achieve an improved understanding of the process, it was decided to focus experimentation on a single part being produced, this was the rear floor pan of the current model Ford Falcon (Part No. 11218) shown below in Figure13. It is important in future research to investigate all of the variables thoroughly in order to determine which ones out of the whole spectrum are in fact the most important and to fully understand how they interact with the process. If this is achieved, then an important step forward will have been taken in the research into sheet metal forming since it is the plethora of variables which is continuing to plague both Engineers and production staff alike.

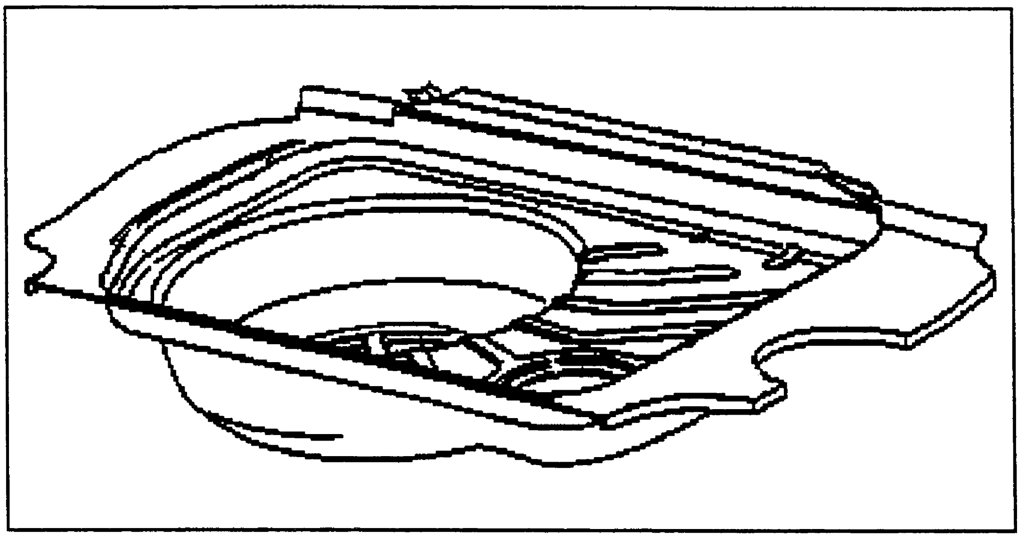


Figure13 - Rear Floor Pan of Ford Falcon

The variables considered was reduced to:

Input Variables

1. Blankholder Gap (Shut Height)

2. Lubrication

3. Blank Position in Die

4. Corner Pressures

Output Variables

1. Flange Length #1

2. Flange Length #2

3. Thickness Strain at the worst location

4. Total peak punch Tonnage

5. Total peak blankholder Tonnage

The input variables were reduced to the four listed above for a number of reasons. Firstly, because they are the ones that die setters used to set a job up and which therefore can be easily controlled by a human operator. This is an important consideration from the point of view of carrying out experimentation. Secondly, from a literature survey and in plant observation of the manufactured part, it appeared that the above mentioned variables were part of a group of variables which had a large influence on how the part was formed from a generic point of view. Lastly, this group of variables, pertained to quality issues characteristic of the part chosen for experimentation.

The shut height has a large influence on how the product is formed (in terms of approaching failure) because it is essentially the displacement of the binder which determines the amount of frictional clamping force which is being applied to the perimeter of the blank. Inturn, it is the magnitude and distribution of this clamping force which controls how and where the metal flows into the die cavity which is the basically the aim of the draw die - to fill the die cavity uniformly with metal which has ideally undergone a uniform amount of plastic deformation.

Lubrication is important because it is a continual point of contention in the press shop as to the effect of its use, particularly with the part in question.

Because the flange lengths were a continual source of rejection (too short) for this part, it was decided to include the blank position as an input variable, one which was believed to have the greatest effect on flange length. Lastly, corner pressures were included as they, like the lubricant, appeared to be a source of controversy as to their effectiveness in affecting the distribution of tonnage.

The output variables are generally quality parameters. The flange lengths must be within tolerance and tonnage and strain were included to try to understand how closely one is approaching the failure limit when forming this part. Total peak punch tonnage and and total peak blankholder tonnage were, in seeming contradiction to previous arguments, considered as output variables because during experimentation, they could not be controlled by the operator, they were measured as the part was being produced as opposed to being specified before the part was being produced. An example of this was that a reduced shut height yielded higher tonnages (see appendix2 results)

CHAPTER 5

MEASURING THE VARIABLES

5.1 Introduction

Having determined what the important variables were, it was then necessary to be able to measure and record them. At the time, the existing systems on the presses were designed for production use and did not always enable one to measure and record data in a way which from a scientific point of view would be deemed sufficiently accurate, however, time and cost constraints meant that the existing equipment had to be used.

5.2 Measuring Shut Height

Shut Height was measured during the experimentation using a counter device which is mounted on the front of the outer slide (ram). The counter is connected to the slide adjustment mechanism of the press. The slide adjustment mechanism uses a worm drive and electric motor to effectively vary the length of the linkage by which force is transmitted from the crown mechanism to the ram (see Figure14). The reason for this adjustment mechanism is to accommodate dies of varying size. It should be noted that the accuracy of the exact reading was not important. The experiments carried out were comparitive and thus as long as there was a discernable and repeatable change in shut height, the experiment yields appropriate trends. During the experiment, the change in shut height was read directly off the afore mentioned counter and recorded manually.

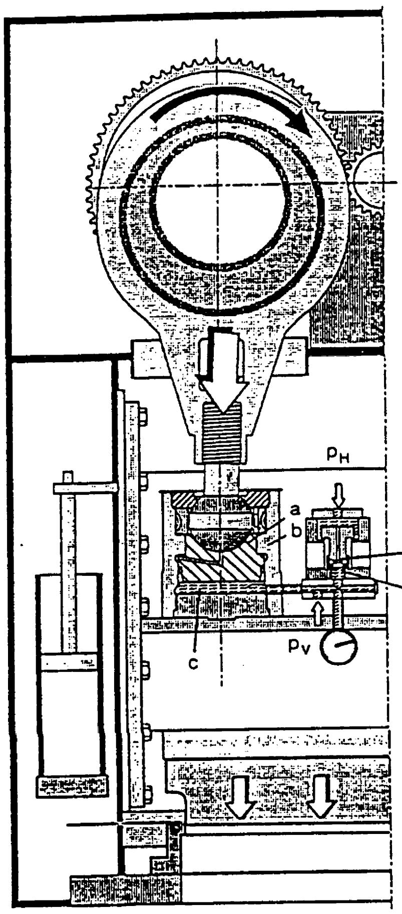


Figure 3. Slide overload protection (normal condition)
a load transmitting piston, b cylinder, c oil cushion, d valve piston (PH retaining pressure, PV preload pressure), e main valve seat

Figure14 - Hydraulic Overload System (Demands on Present Day Presses[43])

5.3 Measuring Lubrication

Lubrication was considered in the first set of experimentation only (see Chapter 7) and in this instance, was only varied such that either it was used or it wasn't, no physical measurements of lubricant film thickness or distribution was attempted.

5.4 Measuring Blank Position in Die

Blank Position was measured using a ruler with a resolution of 0.5 mm. The blank locaters were positioned at one extreme in the first instance and then shifted by some fixed amount in the next instance.

5.5 Measuring Corner Pressures

Corner Pressure was varied and measured by adjusting the air pressure to the oil pump, which controls the overload protection system, using valves in the press column.

5.6 Measuring Flange Lengths

Flange Lengths were measured using a fixture specifically designed and fabricated for the measurement of the latter. This fixture consisted of a large platform with an assembly of components used to center the drawn panel in the same location for each measurement, see Figure15. Initially two and later four rulers of 0.5 mm resolution were attached to this fixture at locations where the part was consistently demonstrating excessive draw-in. Each panel generated during experimentation was placed onto this fixture and the amount of draw-in recorded. In this way, comparisons could be easily made between panels corresponding to different press settings.

5.7 Measuring Thickness Strain at the worst location

Thickness strain was obtained by measuring the change in wall thickness at 4 sections of the panel where the most drawing/stretching was taking place which would correspond to the area of greatest thinning of material, see Figure16. This was achieved using an ultrasonic thickness measurement gauge manufactured by Karl Deutsch Pruef und Messgeraetbau (model number 1070.621). The range of the probe used was between

Figure15 - Measurement Fixture

0.7 mm and 25 mm with a resolution of ± 0.05 mm. The gauge works on the basis of the speed of sound through various materials. It is calibrated by first measuring the thickness of the material in question at a particular location using a micrometer. The gauge is then used to measure the speed of sound through the material at that location using the known thickness. Once the speed of sound through the material is known, it is a simple matter of putting the transducer on any desired location to measure thickness.

5.8 Measuring Tonnage

A common method in industry to measure tonnage is by installing strain gage based transducers in the columns of a press. These transducers measure the amount of elongation which the press columns undergo. By calibrating these devices carefully, it is possible to relate this amount of elongation to the tonnage acting within the die set. Calibration is carried out using four large load cells capable of withstanding the force generated by the press. A load cell is positioned underneath each of the corners of the ram allowing calibration for corner values of tonnage at as many levels as is deemed necessary. This allows operators and staff to monitor tonnage readings continually to note

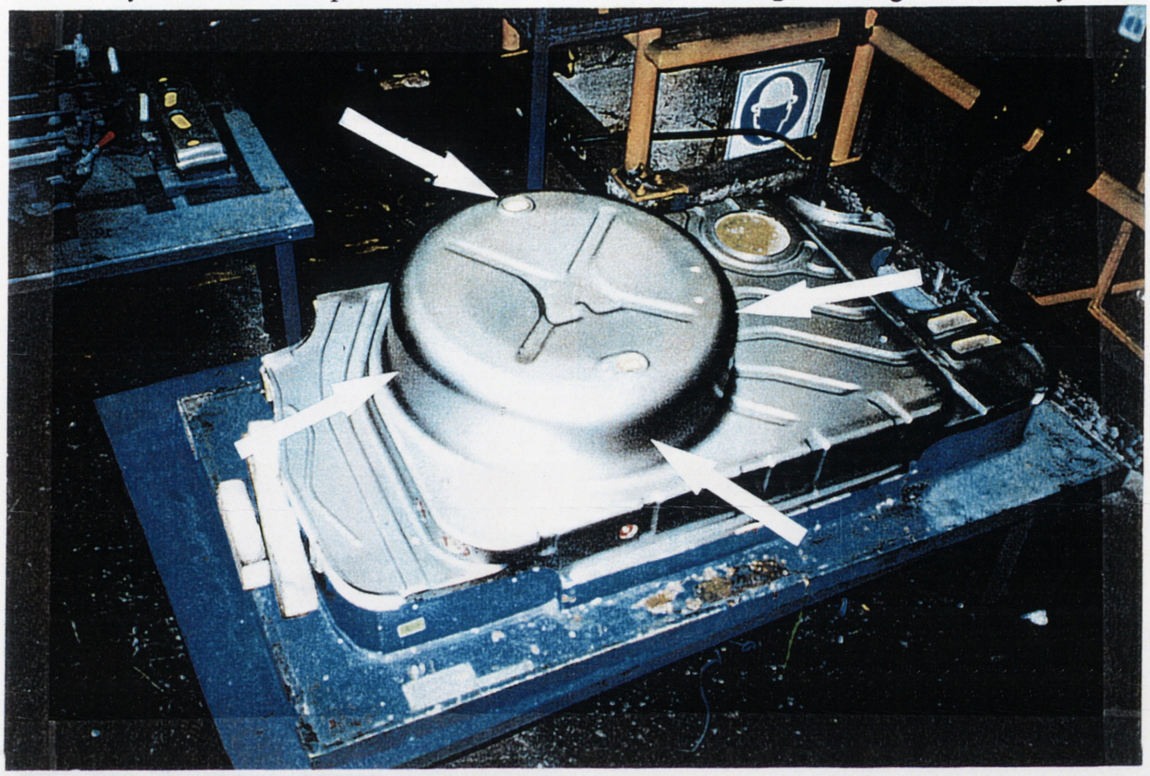


Figure16 - Location of Strain measurement

any drifts which may occur during a production run. The devices also allow one to determine the amount of force required to form a part under certain conditions, thus one could theoretically set limits as to what the acceptable range of "tonnage" is for each corner for both the punch and blankholder of a particular part or die set. Tonnage values were calculated for each of the four corners of the punch and blankholder. In addition to this, total tonnage values were calculated for the punch and blankholder separately. Thus there were ten separate tonnage values calculated for each hit. For the 2 level experiments only the peak punch and blankholder tonnages were recorded. For the 3 level experiments, in addition to the peak tonnage values, corner tonnage values for the blankholder were also recorded. All recordings were made manually during experimentation.

CHAPTER 6

DoE METHODOLOGIES EMPLOYED

6.1 Factorial Experimentation Method

Factorial Experimentation or Designed experimentation as it is sometimes called is a test or series of tests in which changes are made to input variables of a process in a structured and logical fashion so that we may observe and identify the corresponding changes in the values of the output variables. Experimental or Factorial design and Statistical Process Control are two important and related methods used for the improvement and optimization of processes. Statistical Process Control (S.P.C) may be described as being a passive statistical method because the experimenter watches the process, waiting for information that will lead to a useful change. Factorial experimentation on the other hand may be described as being an active statistical method because the experimenter actually performs a series of tests on the process making changes to inputs and observing the resulting changes in the outputs. This information naturally has the ability to lead to process improvement because the true information has been recorded about the process in such a way to produce a real understanding of the process.

6.1.1 Classical Methods

A classical experiment generally involves the investigation of one factor whilst all other factors are held at some constant value. For example, say it is desired to investigate the effects of feed rate and cutting angle on the power consumption of a lathe. In this case, the test variables would be:

1. The two independent variables (factors): feed rate A and cutting angle B

2. The dependant variable (response): power P

The factors A and B would be investigated at two levels (A_1, A_2 , B_1 and B_2) in which case the test would be repeated (replicated) at each test condition to obtain a certain number of observations. These recorded changes in feed rate and cutting angle will give an indication of how they affect the power consumption. The classical approach allows one to determine the effect of A and B on P seperately, however, there are several drawbacks with using this method. The first is that confidence levels cannot be calculated for the estimated effects of A **and** B together. Lastly, it does not estimate the effect of interactions between the two factors on the response variable. This is important because it is quite common to find that it is not just a single factor or factors affecting the response, moreover several factors *combined* affecting the response. Factorial Experimentation allows us to explore such effects in a structured way.

6.1.2 Analysis of Variance

Analysis of variance is an effective technique for analysing experimental data obtained through quantitative measurements. This is especially true if one is unfamiliar with the process from which the data was taken. It is very useful in factorial experiments because there is often several independent sources of variation all of which can be taken into account. When several sources of variation are acting simultaneously on one or more response variables, the variance of the observations is the sum of the variances of the independent sources. Incorporating this, the total variation within an experiment can the independent sources. Incorporating this, the total variation within an experiment can be separated into variations due to each main factor, interacting factors and residual error. The significance of each variation may then be tested.

Variance analysis is based on the laws of probability and so the experiment should be conducted such that the influence of the uncontrollable variables is randomly distributed throughout the test. Using the definition given in [82], the population mean μ is given by:

$$\mu = \frac{\sum_{i=1}^{n} x_i}{N} \quad \text{.........(19)}$$

where N = sample population and x_i refers to individual values. The population variance is defined as:

$$\sigma^2 = \frac{\sum_{i=1}^{N}(X_i - \mu)^2}{N} \quad \text{.........(20)}$$

where X_i refers to individual values.

In analysing the variations in factorial experiments, the mean square is defined by the ratio of the sum of squares to the degrees of freedom as defined below:

$$\text{Mean squares} = \frac{SS}{DF} \quad \text{.........(21)}$$

where SS = sum of squares and DF = degrees of freedom. The sum of squares is a measure of the total variation in the data - the sum of all squared deviations about the grand mean. In the context of Factorial Experimentation, the degrees of freedom refers to the number of levels at which a variable is being investigated minus one. The following are the relationships for the determination of the sum of squares SS in an experiment where only one factor at several levels is to be investigated:

$$SS_{total} = \sum x^2 - \frac{T^2}{N} \qquad (22)$$

where $\sum x^2$ = sum of squares of all observations

T = grand total of all observations

N = total number of observations

If experimental data about a process is collated into a table (table1 for example) and the different levels of one of the variables is to be represented by columns, then:

$$SS_c = \text{SS between column means} = \frac{\Sigma T_c^2}{n} - \frac{T^2}{N} \qquad (23)$$

where T_c = total of each column

c = number of columns

n = total number of observations

$SS_{residual}$ = SS within the columns, or the experimental error

$$= SS_{total} - SS_c \qquad (24)$$

In this way, the total variation is broken down into two sources of variation; variations within the columns (experimental error) and the variation between the columns (signal change). Each of these variations, which are in terms of the sum of squares, reduces to the mean squares when they are defined by their corresponding degrees of freedom. The ratio of any two of these mean squares provides the basis for the F test of significance which is used when comparing two population variances (or standard deviations). In the case that the populations under investigation are normal, the procedures used in analysis of the variables are based on the F distribution. For a more detailed description of the F test, see Devore [25]. When the *F* test is applied to the ratio of the Mean Square of columns to the Mean Square of residual, it will indicate whether a significant difference exists between the columns or whether the observed difference is due to chance or the experimental error alone.

Computations involved in the analysis of variance are relatively simple for single and two-factor experiments. However, as the number of factors increases, so to does the computations. The analyses for two and three factor experiments is shown below, the necessary relationships to compute various sums of squares and the actual derivations may be found in standard statistics books [25],[82].

6.1.3 Two Factor Experiments

For a two factor experiment we continue with the example used in 6.1.1, the results from a two factor experiment might be:

		Cutting Angle		
		B_1	B_2	T_r
Feed Rate	A_1	5 3	8 1	17
	A_2	6 4	2 1	13
	T_c	18	12	

Table1

the following nomenclature is adopted:

A_1 = feed rate 1

A_2 = feed rate 2

B_1 = cutting angle 1

B_2 = cutting angle 2

r = number of rows = number of feed rates = 2

c = number of columns = number of cutting angles = 2

N = 8, total number of observations or tests

n = 2, number of replications (or number of tests) at each test combination

$T = \sum X_i$, where x is the value of each observation, in this case power = 30

$$\frac{T^2}{N} = \frac{900}{8} = 112.5 \quad \text{.......(25)}$$

T_r = total of each row

T_c = total of each column

$$\sum x^2 = 5^2 + 3^2 + 8^2 + 1^2 + 6^2 + 4^2 + 2^2 + 1^2 = 156 \quad \text{.......(26)}$$

$$\sum T_c^2 = 18^2 + 12^2 = 468 \quad \text{.......(27)}$$

$$\sum T_r^2 = 17^2 + 13^2 = 458 \quad \text{.......(28)}$$

$$\sum T_{cr}^2 = 8^2 + 9^2 + 10^2 + 3^2 = 254 \quad \text{.......(29)}$$

The following are sums of squares for the sources of variation:

1. Among columns (cutting angle):

$$SS_c = \frac{\Sigma T_c^2}{nr} - \frac{T^2}{N} = \frac{468}{2 \times 2} - 112.5 = 4.5 \quad \text{.......(30)}$$

2. Among rows (feed rate):

$$SS_r = \frac{\Sigma T_r^2}{nc} - \frac{T^2}{N} = \frac{458}{2 \times 2} - 112.5 = 2 \ldots\ldots (31)$$

3. Column-row interaction:

$$SS_{cr} = \frac{\Sigma T_{cr}^2}{n} - \frac{T^2}{N} - SS_c - SS_r = \frac{254}{2} - 112.5 - 4.5 - 2 = 8 \ldots\ldots (32)$$

4. Total:

$$SS_{total} = \sum x^2 - \frac{T^2}{N} = 156 - 112.5 = 43.5 \ldots\ldots (33)$$

5. Residual:

$$SS_{resiual} = SS_{total} - SS_c - SS_r - SS_{cr}$$

$$= 43.5 - 4.5 - 2 - 8$$

$$= 29 \ldots\ldots (34)$$

Source of variation	Sum of squares SS	Degrees of freedom DF	Mean square MS (SS/DF)	Mean-square ratio MSR ($MS/MS_{residual}$)	Minimum MSR required for factors to be significant at 90% confidence $F_{0.1;1;4}$
Among Columns	4.5	c-1 = 1	4.5	0.62	4.54
Among rows	2	r-1 = 1	2	0.27	4.54
Column-row interaction	8	(c-1)(r-1)=1	8	1.1	4.54
Residual (experimental) error	29	Total - sum of previous = 4	7.25		
Total	43.5	*N*-1 = 7			

Table2 - Example of Two Factor Factorial Experiment Results

From the results given in table2 above, it can be concluded with 90 percent confidence that neither the feed speed nor the cutting angle have a significant effect on the power consumption. The insignificant interaction effect also means that the feed rate is not dependant upon the cutting angle.

6.1.4 Three Factor Experiments

A similar methodology will be applied for a three factor experiment. In this example, several surface defects are being experienced on an automotive panel. It is felt that the three variables which may be having a significant effect on the surface finish are:

1. Draw Speed of Ram
2. Blankholder Force
3. Steel Type

A number of panels were tested and the experimental plan showing the test combinations is shown below. The severity of surface defects was monitored as follows:

0 = not visible to eye

1 = visible to eye but not significant after painting

2 = visible to eye and certain to show after painting

			Columns	
			Draw Speed	
		Groups	c1	c2
Rows	Steel Type A1	Force B1	0	2
		Force B2	0	2
	Steel Type A1	Force B1	2	0
		Force B2	1	2

Table3

the following nomenclature is adopted:

r = 2; A_1 and A_2

g = 2; B_1 and B_2

c = 2; C_1 and C_2

N = 8, total number of observations or tests

n = 1, number of replications (or number of tests) at each test combination

$T = \sum x_i$, where x_i is the value of each observation, in this case defects

$= 0 + 2 + 0 + 2 + 2 + 0 + 1 + 2$

$= 9$ ....(35)

$\frac{T^2}{N} = \frac{9^2}{8} = 10.125$ ....(36)

The following are the sums of squares for the sources of variation:

1. Among columns:

$$SS_c = \frac{\sum T_c^2}{nrg} - \frac{T^2}{N} = \frac{3^2 + 6^2}{1 \times 2 \times 2} - \frac{81}{8} = 1.125 \quad \text{.......................................(37)}$$

2. Among rows:

$$SS_r = \frac{\sum T_r^2}{ncg} - \frac{T^2}{N} = \frac{(2+2)^2 + (2+1+2)^2}{1 \times 2 \times 2} - \frac{81}{8} = 0.125 \quad \text{......................(38)}$$

3. Among groups:

$$SS_g = \frac{\sum T_g^2}{nrc} - \frac{T^2}{N} = \frac{(2+2)^2 + (2+1+2)^2}{1 \times 2 \times 2} - \frac{81}{8} = 0.125 \quad \text{......................(39)}$$

4. Column-row interaction:

$$SS_{cr} = \frac{\sum T_{cr}^2}{ng} - \frac{T^2}{N} - SS_c - SS_g = \frac{2^2 + 1^2 + 2^2 + 4^2}{1 \times 2} - \frac{81}{8} - 1.125 - 0.125$$

$= 3.125$ ....(40)

5. Column-group interaction:

$$SS_{cg} = \frac{\sum T^2_{cg}}{nr} - \frac{T^2}{N} - SS_c - SS_g = \frac{2^2+1^2+2^2+4^2}{1\times 2} - \frac{81}{8} - 1.125 - 0.125$$

$= 1.125$ ....(41)

6. Row-group interaction:

$$SS_{rg} = \frac{\sum T^2_{rg}}{nc} - \frac{T^2}{N} - SS_r - SS_g = \frac{2^2+2^2+2^2+3^2}{1\times 2} - \frac{81}{8} - 0.125 - 0.125$$

$= 0.125$ ....(42)

7. Column-row-group interaction:

$$SS_{crg} = \frac{\sum T^2_{crg}}{n} - \frac{T^2}{N} - SS_c - SS_r - SS_g - SS_{cr} - SS_{cg} - SS_{rg}$$

$$= \frac{2^2+2^2+2^2+1^2+2^2}{1} - \frac{81}{8} - 1.125 - 0.125 - 0.125 - 3.125 - 1.125 -$$

0.125

$= 1.25$ ....(43)

8. Total:

$$SS_{total} = \sum x^2 - \frac{T^2}{N} = (2^2 + 2^2 + 2^2 + 1^2 + 2^2) - \frac{81}{8} = 5.428$$

9. Residual or error:

$SS_{residual} = SS_{total}$ - all previous SS

$= 5.4288 - (1.125 + 0.125 + 0.125 + 3.125 ++ 1.125 + 0.125 + 1.25)$

$= -1.57$

Because there is only one replication, there is no error as residual error is caused by replicating the experiments under the same conditions. Other errors may be induced by the operator or designer, these are usually lost in the interactions.

	Source of variation	Sum of squares SS	Degrees of freedom DF	Mean square MS (SS/DF)	Mean square ratio MSR	MSR min 90% $F_{0.1;v1;v2}$	95% $F_{0.1;v1;v2}$	97.5% $F_{0.1;v1;v2}$
Main Factors	1.Among Columns	1.125	c-1 = 1	0.888	1.25	2.24	2.85	3.5
	2.Among Rows	0.125	r-1 = 1	8	11.25	3.05	4.49	6.12
	3.Among groups	0.125	g-1 = 1	8	11.25	3.05	4.49	6.12
Interacting Factors	4.Column row interaction	3.125	(c-1)(r-1) = 1					
	5.Column group interaction	1.125	(c-1)(g-1) = 1					
	6. Row group interaction	0.125	(r-1)(g-1) =1					
	7.Column row group interaction	1.25	(c-1)(r-1) (g-1) = 1					
	8.Residual Error, (4+5+6+7)	5.625	1+1+1+1 = 4	0.7111				

Table4 - Example of Three Factor Factorial Experiment Results

On the basis of the values given in table4 above, one would conclude that the draw speed did not have a significant effect on the panel quality whilst the blankholding force and steel type had quite a significant effect. One would therefore conclude that it is the steel type and blankholding force which are causing the defects in the panel.

6.2 Yates Algorithm

In carrying out the corner pressure experiments (see chapter9), it was necessary to incorporate four factors. This would have been extremely time consuming and complicated using the ANOVA method described above, for this reason, the Yates method was adopted [5]. The Yates method produces the same results as a conventional ANOVA method. It involves arranging all the experimental combinations and their respective results in a tabular matrix. The variables are represented by columns whilst the experiments (combinations of variables) are represented by rows.

For a two level experiment, the variables are designated as being either positive or negative. One level at which a variable is set is designated as being positive whilst the second level is designated as being negative. All combinations are computed. The sign for the interactions is then calculated by multiplying the sign of the constituent variables. The data is then summed according to the signs, all the positive values are added and then all the negative values are added. The difference is then taken and all the differences are compared for each set of interactions. The relative effects of each variable and variable interactions may then be easily determined. For example, in appendix8, one can see that there were 16 experiments. The inputs or factors are classified simply as A,B,C and D. For experiments 1 through to 16, all of the variables are assigned either a plus or a minus sign. All of the combinations are then determined by multiplication of the signs as described above. For example, AB for experiment 13 on the front edge is a +. This is determined by $A \times B = + \times + = +$. All of the data for each combination has been added according to the sign. For example, the sum of the pluses for AB is 948.4 whilst the sum of the minuses is 1213.5. The difference is 265.1 so in comparison to the rest of the differences of plus and minus, the number is high. This means that the effect of the combination of variable A and B is high.

CHAPTER 7

2 LEVEL FACTORIAL EXPERIMENTS

7.1 Introduction

The purpose of the factorial experiments was to identify which variables have the most effect on the quality parameters of a particular part which has traditionally been troublesome. In this case, the part happened to be the rear floor pan of the current model Ford Falcon sedan Part No.11218. The recurring problems that the part had were splitting in the wall of the draw and short flanges, see Figure17. Shortly before the experiments were carried out, the blankholder was re-machined and the contact surface made true. This reduced the splitting problem with this part however short flanges were still occurring at that stage.

7.2 Variables

The variables considered were those outlined at the end of section 4.4. This decision was made based on observation of press shop operations over a 5 month period. It was concluded at the end of this period that these variables were the ones which had the greatest effect on the output variables. The output variables chosen appeared to have the greatest impact on part quality.

Input Variables

1. Blankholder Gap (Shut Height)
2. Lubrication
3. Blank Position in Die

4. Corner Pressures

Output Variables

1. Flange Length #1

2. Flange Length #2

3. Thickness Strain at the worst location

4. Total peak punch Tonnage

5. Total peak blankholder Tonnage

7.3 Experimental Procedure

The experiment was carried out as a 2 level, 3 factor factorial experiment with three repetitions made for each experiment. The experimental plan is shown below in table5.

Inputs	Shut Height (in)	Lubricant	Blank Position	Corner Pressure
Experiment 1	62.537	Roll Coater	Position #1	304 kPa
Experiment 2	62.55	Roll Coater	Position #1	304 kPa
Experiment 3	62.55	Roll Coater	Position #1	405 kPa
Experiment 4	62.537	Roll Coater	Position #1	405 kPa
Experiment 5	62.55	Roll Coater	Position #2	304 kPa
Experiment 6	62.537	Roll Coater	Position #2	304 kPa
Experiment 7	62.55	Roll Coater	Position #2	405 kPa
Experiment 8	62.537	Roll Coater	Position #2	405 kPa
Experiment 9	62.55	Mill Oil	Position #1	304 kPa
Experiment 10	62.537	Mill Oil	Position #1	304 kPa
Experiment 11	62.55	Mill Oil	Position #1	405 kPa
Experiment 12	62.537	Mill Oil	Position #1	405 kPa
Experiment 13	62.55	Mill Oil	Position #2	304 kPa
Experiment 14	62.537	Mill Oil	Position #2	304 kPa
Experiment 15	62.55	Mill Oil	Position #2	405 kPa
Experiment 16	62.537	Mill Oil	Position #2	405 kPa

Table5 - Press Settings with corresponding Experiment Number

The experiment was carried out on a weekend when production was not running. Three people were involved with the experiment. The press was cycled over to begin with and a few parts were produced which were not part of the experiment in order to simulate the experiment taking place under normal production conditions. The experiment was carried

Figure17 - Short Flange

out by running three panels for each group of press settings in a row as this was thought to be a closer reflection of normal press operating conditions and lead to a more accurate representation of the changes in output variables which could reasonably be expected. In other words, to not have produced panels during the experiment in this fashion would have caused the generation of data which could not have been used to arrive at any logical conclusion about the process. To truly achieve the random principle in experimentation, it would have been necessary to take measurements over a whole production run which was not possible within the framework of this project. It would have been possible to vary the settings within the experiment however this was not practical in the industrial setting. Tonnage was recorded for each panel. The panels were then placed on the fixture one at a time and the thickness and flange lengths were measured as described in chapter 5. During this time, adjustments were being made to the press in line with the experimental plan, see table5. The panels were then put to one side and the next three panels were run through the press with the second group of settings. This procedure was followed until all of the experiments with the exception of the mill oil experiments had been completed.

The first eight experiments all included lubricant as present. The experiments with mill oil and no lubricant were then commenced however it was discovered that the part could not be made without lubricant and that to continue without lubricant would risk damaging the die and put the toolmaker and supervisor at unnecessary risk.

7.4 Summary of Results

All numerical results are given in appendix1& 2. Three of the inputs were shown to have significant effects on the outputs, the exception being corner pressure. With regards to wall thickness, there was not very much variation either within an individual experiment or between groups of settings (other individual experiments). Lubrication on the other hand appeared to have a profound effect on all of the outputs. This was demonstrated most clearly when it was discovered that the part could not be made with mill oil only. There even appears to be variation within an individual experiment and this is believed to be caused by changes to the property of the lubricant due to change of die surface temperature.

Blank Position appeared to have a significant effect on the flange lengths however the same cannot be said for the wall thickness or tonnage (see appendix2). The effect on flange length is more than it appears at first glance. It would seem obvious that if one was shifting the blank in one direction, then the flange in that direction would be large, indeed this was the case, however, shifting the blank along one axis (left to right facing the front of the press) also affected the flange lengths along the perpendicular axis (front to back facing the front of the press). This is believed to be caused by either more or less frictional clamping force being applied to certain corners of the blank caused by its lateral shift with respect to the blankholder causing either more or less metal to flow into the die cavity as the case may be.

Corner Pressure did not appear to have a significant effect on any of the output variables with a few exceptions. It is believed that the reason for this is that all four corner pressures were changed simultaneously to the same value. This actually corresponds to either a higher or lower overall force being applied by the binder. From the above discussion, it is clear that flange lengths were still a problem since they were sensitive to both shut height, lubricant and blank position. Wall thickness on the other hand did not show any sensitivity to any of the inputs, remaining stable throughout experimentation.

The tonnage values recorded merely reflected the groups of settings used. When lower shut heights were trialed, the tonnage, understandably increased and vice versa.

7.5 Summary of Analysis

All numerical results are given in appendix1& 2. The results of experiments 13 and 14 showed that the wall thickness was extremely sensitive to lubrication and that the die in its current state could not be run without it being present. This simplified the experimentation allowing the analysis to be carried out as a three factor experiment, the three inputs now being Shut Height, Blank Position and Corner Pressure. The results from appendix2 show that the wall thickness of the draw is relatively stable. This is indicated by the fact that at all levels of confidence, that is 90%, 95% and 97%, there was no significant effect of any one input variable or interaction between combinations of input variables on any of the wall thicknesses. The only exception to this is an apparent effect of shut height on wall thickness at location G4.5. This is believed to be attributed to experimental error since wall thickness measurements were more difficult to obtain at location G4.5. The variance calculated for the wall thickness values was very low, 0.0003 mm at the high level and zero at the low level.

Graphical Results are given in appendix3. With reference to the two dimensional graphs numbered 1 to 12, one may appreciate that there are no trends suggesting that any input variable or combination of input variables has any particular effect on the wall thickness. The three dimensional graphs numbered 55 to 64 do indicate a degree of interaction however the gradients are actually small, the change in height or thickness being in the order of 0.01 to 0.025 mm.

The results from appendix2 (tables7,8) indicate that shut height has a very strong effect on both punch and blankholder tonnage. This holds true at all levels of confidence. In other words, one is 97.5% confident that shut height has an effect on tonnage. However, no other input variable nor combination of input variables shows any effect with punch tonnage or blankholder tonnage. The highest variance calculated for the tonnage values was 12 tons and the lowest was 0. The average however was 3 tons which in the context of pressing is quite low. The fact that punch tonnage is affected to a large extent by the shut height means that there is a real possibility of damaging the press by setting the shut height too low. If this is the case, then quality will also be affected since part quality is dependant upon press quality [43].

The two dimensional graphs reflect clearly the findings of the analysis of variance. Graphs 45 to 48 show that an increase in shut height relieves tonnage values considerably. For example, the largest change in tonnage for a ten thousandth of an inch change in shut height was 60 tons whilst the smallest change in tonnage for the same change in shut height was 30 tons. This trend is also reflected by the three dimensional graphs. Graphs 65 through 68 basically show that although the combination of corner pressure and shut height have a small effect on the tonnage, it is the lower shut height itself which yields a much higher tonnage.

The results from appendix2 (table1) indicate that there is a significant interaction between all three input variables and the flange length on the side edge at a 90% level of confidence. The interaction is strongest between blank position and flange length followed by shut height and corner pressure. At a 97.5% level of confidence, corner pressure shows no interaction with flange length on the side edge. The highest variance value for flange length on the side edge was 18 mm whilst the lowest was 1.3 mm. However, the average variance was 6 mm. This is a reasonably high value, however only 3 repetitions were allowed and it is anticipated that this value could be substantially lowered statistically by carrying out many more repetitions.

The results from appendix2 (table2) also show that shut height has a significant effect on flange length on the front edge and that corner pressure has an effect on flange length on the front edge. This is for a 90% level of confidence. At a 97.5% level of confidence only blank position demonstrates a significant effect with the flange length to the front edge. The largest variance for this output variable was 11 mm whilst the smallest was 0.25 mm. However, the average variance of 2.8 mm is significantly lower than that for the flange length to the side edge. As with the flange length on the side edge, the average value of variance is reasonably large however, the results might have yielded a lower variance with more repetitions.

The two dimensional graphs in appendix3 numbered 13 through 24 reflect the above findings, but also indicate some unusual trends. For example, graphs 21 to 24 show that increasing the shut height yields a larger flange to the front edge but yields a smaller flange to the side edge. It also indicates that the effect is more marked for the side edge than it is for the front edge. Graphs 17 to 20 indicate that as a general rule, the flange lengths on both edges are reduced by increasing the corner pressure. Graphs 13 to 16 show that larger flange lengths on both edges are obtained at higher values for blank position though as with shut height, the effect is more marked with the flange length on the side edge. The three dimensional graphs numbered 49 through to 52 show that the effect of corner pressure is nowhere near as marked as it is for shut height, however the combination of blank position and shut height is quite significant as shown by graphs 53 and 54.

7.6 Conclusions

The basic conclusions of the 2 level factorial DoE were quite interesting from an academic point of view and matched the opinions of experienced toolmakers. The first and obvious conclusion was that lubricant is absolutely necessary for the part. For this reason, it was taken out of consideration as an input variable since it could not be varied in a controlled manner during an experiment. It was simply included in the experiment in order to ensure that parts were formed.

The second point discovered was that since the die had been reworked and hard chromed, the actual part had become quite stable with respect to wall thickness and that there was no significant interaction between any of the input variables and the wall thickness of the drawn profile. This effectively meant that the only remaining concerns for this part were the flange lengths.

The third point discovered was that the blank position had by far the greatest impact on the length of the flanges on both the front and the side edge. Comparing the data from appendix2 (tables1,2) for experiments 4 and 8 for example, one finds that a shift in blank position made a difference of $\delta = 4$ mm for the side edge and $\delta = 11$ mm for the front edge. This may seem small, however, it must be understood that if there is any shortage of material at either of these edges succeeding the trimming and flanging operations, then the panel will be automatically rejected since these flanges are required as attachment points for spot welding to the remainder of the chassis. The second most important factor, with less severity, however still significant, was shut height. It was initially expected that shut height would have the most impact and although the effect is high, it is nowhere near as marked as for blank position. If one thinks about this, it becomes obvious when considering the relative gripping of the blankholder. By shifting the blank one way or the other, material will either be gripped more or less on the basis of surface area regardless of shut height - hence the effect is more marked for blank position as mentioned earlier.

Corner pressure was set at two levels as with the other variables however all four corner pressures were set to the same value. With this arrangement, the effect of corner pressure was barely significant. It was suggested that if one was to alter the corner pressure settings with respect to each other, corner pressure would indeed show some significant interaction. For this reason, it was intended to investigate the effects of corner pressure more fully with a 4 factor 2 level factorial experiment with settings above and below those trialed for the screening DoE.

In light of this, it was also decided to carry out a multilevel factorial experiment incorporating only shut height and blank position at 3 levels. The results of these two experiments was then expected to yield enough data to generate a system response surface which would determine the safe parameter space and/or "operating window" (unknown at the time) which inturn may be issued to production staff in the forms of minimum/maximum settings displayed on the Process Control Plan (PCP) used by production staff to set each job up.

CHAPTER 8

3 LEVEL FACTORIAL EXPERIMENTS

8.1 Introduction

As mentioned in the above section, the purpose of the 2 level factorial screening experiments was to identify which variables had the most effect on the quality parameters of the part. These experiments were duly completed with the results discussed above. One of the facts which became glaringly obvious during the 2 level experiments was that the part could not and would not run without lubricant. Later experimentation once more re-enforced the knowledge that the part is extremely sensitive to lubricant (see section 7.4).

Another important point borne out of the previous factorial experiments was that corner pressure appeared to have a rather limited effect on the flange lengths *if* all the corner pressures were set to the same value leaving the two most influential variables for this part to be shut height and blank position. For this reason, the 3 level factorial experiments only incorporated shut height and blank position and no attempt was made to alter the lubrication condition or the corner pressure settings.

The purpose of carrying out a 3-level experiment was to try to determine the nature of the system response surface for each flange length and from it, deduce the 'safe region of operation' . The aim was then to deduce which 'regions of operation' overlapped from flange length to flange length and then to specify this overlapped region as the overall safe region of operation.

8.2 Variables

The variables considered as mentioned above were as follows:

Input Variables

1. Shut Height
2. Blank Position in Die

Output Variables

1. Flange Length to side edge
2. Flange Length to front edge
3. Flange Length to left edge
4. Flange Length to rear edge
4. Total peak punch Tonnage
5. Total peak blankholder Tonnage
6. Left Rear Corner Tonnage
7. Right Rear Corner Tonnage
8. Right Front Corner Tonnage
9. Left Front Corner Tonnage

To get an even better understanding of the effect of shut height, the counter on the slide was used to change between three levels of ram displacement. Even though the exact blankholder gap was unknown, the relative effect of changing height could be once again gauged. The blank position was once again varied by shifting a locater which located the blank between three levels, left to right facing the direction of work flow.

As with the previous experiment, both Flange Lengths were measured using the same fixture. Two additional rulers were attached to the fixture to enable flange length measurements to the left and rear edges. Tonnage was measured again using the same tonnage monitors. This time the corner tonnages for the blankholder were also measured in addition to the peak punch tonnage and the peak blankholder tonnage.

8.3 Experimental Procedure

The experiment was carried out as a 3 level, 2 factor factorial experiment with three repetitions made for each experiment. The experimental plan is shown below in table6.

Inputs	Shut Height (inches)	Blank Position (millimetres)
Experiment 1	62.527	374
Experiment 2	62.56	374
Experiment 3	62.527	404
Experiment 4	62.56	404
Experiment 5	62.57	374
Experiment 6	62.527	380
Experiment 7	62.57	380
Experiment 8	62.57	404
Experiment 9	62.56	380

Table6

The experiment was carried out before day shift production commenced. Three people were once more involved with the experiment and the format for running panels through the press and altering the press settings in accordance with the experimental plan was followed in the same manner as with the 2 level experiments. Tonnage was recorded for each panel however in this series of experiments, corner tonnages were also recorded.

For the 2 level experiments, only the draw press was required for experimentation. However, to achieve the aims of the 3 level experimentation, it was necessary to complete all operations and achieve a finished part. The reason for this was that at the time, there was no knowledge of the limits to which draw-in could go before a short flange would result. To this end, all of the panels used for experimentation were run through all operations. This made it possible to determine which groups of press settings were in fact satisfactory and which were not. It also enabled us to determine what the minimum acceptable amount of draw-in after the first operation is which would be very useful for future use. The full experimental results for the three level experiments is in appendix4.

8.4 Summary of Results

Many of the discoveries made in the 2 level set of experiments were once more evident in the 3 level experiments however there were some subtle differences. Both shut height and blank position both had very strong effects on flange lengths on all four sides of the panel. The difference was that on the left and side edge, the effect of blank position was greater than the effect of shut height whilst on the front and rear edge, the reverse was shown to be true. This can be seen when comparing the MSR values of the effects of Blank Position and Shut Height in tables1 to 4 of appendix5. As with the 2 level experiments, the changes in shut height were reflected in either increased or decreased tonnage values (higher tonnage for lower shut height and vice versa), however, it was found that although the variance for tonnage was quite low, in comparison to the two level experiments, the tonnage values had changed quite considerably. For this reason, tonnage would not be recorded in the next set of experiments. The reason for this was that tonnage for the purposes of industrial experimentation is considered to be an output. As such, nothing can be done with it to alter the way the process is operating. The only practical use of tonnage measurements was for verification of FE modelling and since the values were thought to be unreliable due to lack of maintenance and calibration on the part of the Ford Motor Company, they were ignored. The minimum draw-in data for satisfactory parts was used in conjunction with three dimensional response surfaces obtained for each edge of the panel using all of the experimental data, to determine graphically, which combinations of the inputs (shut height and blank position) would yield an acceptable panel. This information was combined for all sides of the panel to obtain an overall chart demonstrating which combinations of the inputs yielded a satisfactory part.

8.5 Summary of Analysis

All numerical results are given in appendix4 & 5. Graphical results are given in appendix6. As previously mentioned, all the panels from the 3 level experiments had to be processed to determine which ones in fact were acceptable and which were not. The results of this showed that the settings for all experiments with the exception of 4 and 8 gave acceptable panels with varying degrees of quality. In the case of experiment 4 and 8, short flanges were experienced. All the other experiment settings yielded acceptable flange lengths however slight wrinkling was detected where the flanges are usually short (front edge). This was true for all experiments however the best results were achieved with the settings from experiment1. There was very minimal wrinkling with this combination of settings.

The above information was used to determine what the minimum amount of draw in after the first operation is for an acceptable part for all four edges. This was achieved by comparing the amount of draw in for acceptable parts with the amount of draw in for unacceptable parts. The results of this are shown in appendix7.

The information for flange lengths for each experiment were used to plot three dimensional graphs of blank position and shut height vs flange length for all four edges. These four graphs are shown in appendix6 numbered 1 through 4. It may be readily appreciated that the graphs do not all slope in the same direction. This is reflected by the numerical results which show that the flange lengths to the left and side edge are largely affected by blank position whilst the flange lengths to the front and rear edge are largely affected by shut height. One may appreciate furthermore that the cut off values given in appendix7 will appear as planes in their respective three dimensional graphs. Also, these planes will intersect the three dimensional surfaces along a certain line. This line would divide the surface into a region which is safe - that region above the line and a region below the line of intersection - the forbidden zone or unsafe region. Lastly, all four "safe" regions corresponding to the particular flange lengths will overlap yielding an overall "safe" region or "window" of operation which is made up of some combination of shut heights and blank position.

It is this overall region which we are interested in because this is the information that production personnel may readily use and appreciate. It is the information yielded by this graph which is used to determine what "safe" P.C.P settings are. The graph developed from the four three dimensional graphs is labelled graph5 in appendix6. One can readily interpret some important points. One of them is that it is not recommended to operate above a blank position of 380 mm. This is because at this value, one is close to the front edge line jutting into the safe zone. One might argue that operating above 380 mm blank position is possible with some merit, however, there is less scope for shut height adjustment before the left edge flange line is violated. A "safe" and reasonable setting then, would be a blank position of approximately 376 mm and a shut height setting of 62.55 inches.

It was provisionally decided to operate at the lower physical blank position limit - that of 374 mm and to operate at shut heights of between 62.527 and 62.555 in. This was because shop-floor observation revealed that the tendancy of the part to develop wrinkling decreased as the shut height was lowered.

8.6 Conclusions

The industrial focus of this project meant that the needs of the industrial partner had to be satisfied along with the academic needs. As far as production was concerned, it was short flanges and wrinkling to the rear edge as well as short flanges to the left edge which was a concern. For this reason, it was suggested that the settings deduced in 8.5 be adopted, trialed and proven out. The balance was simply this, operate at a high enough shut height to avoid short flanges consistently but at a low enough shut height to avoid wrinkling. The above results yielded enough information to make some compromise and the actual values have been trialed and continually used for at least four separate runs. The results have been promising, scrap levels have reduced considerably, so much so that the part is now no longer on the top ten items on the scrap list, where it once held a conspicuous sixth place.

CHAPTER 9

CORNER PRESSURE FACTORIAL EXPERIMENTS

9.1 Introduction

As was pointed out in the two-level analysis earlier, corner pressure appeared to have a rather limited effect on the flange lengths *if* all the corner pressures were set to the same value. Setting all corner pressures at the same level is to make a very fine adjustment to the shut height. Essentially, the binder or clamping pressure is simply being adjusted. However, matters become considerably more complex when different combinations of corner pressure are tried. This has long been an accepted fact in the press shop, however, there is no real understanding as to what the effect of changing corner pressure in certain combinations is.

For this reason, a corner pressure factorial experiment was carried out to try to determine what the effects of certain corner pressures are, if there are any interactions and how strong both of the latter actually are.

9.2 Variables

The variables considered as mentioned above were as follows:

Input Variables

1. Left Rear Corner Pressure
2. Right Rear Corner Pressure
3. Right Front Corner Pressure

4. Left Front Corner Pressure

Output Variables

1. Flange Length to side edge
2. Flange Length to front edge
3. Flange Length to left edge
4. Flange Length to rear edge

As with the previous two experiments, Flange Lengths were measured using the same fixture. Additional Markings were made to the fixture to enable the initial and final position of each corners of the blank to be recorded. The reason for this was that previous experiments showed an uneven movement of the corners leading to a skewed appearance of the part succeeding the drawing operation. It was also necessary from an FE modelling point of view to be able to monitor exactly how the corners of the blank move - it makes comparison between simulation and experimental results considerably easier. However, during the experiment, the corners of the panel were found to exceed the scale of the corner markings and hence no corner draw-in values could reliably be obtained.

9.3 Experimental Procedure

The experiment was carried out as a 2 level, 4 factor factorial experiment with three repetitions made for each experiment. The experimental plan is shown below in table7.

Inputs	Left Rear C.P	Right Rear C.P	Right Front C.P	Left Front C.P
Experiment 1	200 kPa	200 kPa	200 kPa	200 kPa
Experiment 2	200 kPa	200 kPa	200 kPa	300 kPa
Experiment 3	200 kPa	200 kPa	300 kPa	200 kPa
Experiment 4	200 kPa	200 kPa	300 kPa	300 kPa
Experiment 5	200 kPa	300 kPa	200 kPa	200 kPa
Experiment 6	200 kPa	300 kPa	200 kPa	300 kPa
Experiment 7	200 kPa	300 kPa	300 kPa	200 kPa
Experiment 8	200 kPa	300 kPa	300 kPa	300 kPa
Experiment 9	300 kPa	200 kPa	200 kPa	200 kPa
Experiment 10	300 kPa	200 kPa	200 kPa	300 kPa
Experiment 11	300 kPa	200 kPa	300 kPa	200 kPa
Experiment 12	300 kPa	200 kPa	300 kPa	300 kPa
Experiment 13	300 kPa	300 kPa	200 kPa	200 kPa
Experiment 14	300 kPa	300 kPa	200 kPa	300 kPa
Experiment 15	300 kPa	300 kPa	300 kPa	200 kPa
Experiment 16	300 kPa	300 kPa	300 kPa	300 kPa

Table7

The experiment was carried out on a weekend when no production was required. Two people were involved with the experiment and the format for running panels through the press and altering the press settings in accordance with the experimental plan was followed in the same manner as with the 2 and 3 level experiments. Only flange lengths were measured in single repetitions in this set of experiments. As described above, the minimum draw-in data had already been established and it was only necessary to use the draw press. The full experimental results for the corner pressure factorial experiments is given in appendix8.

9.4 Summary of Results

The data shown in appendix8 showed that there were three combinations of input variables which consistently demonstrated a very strong effect on the flange lengths to all four sides of the panel. These combinations were the Left Front and Left Rear corner pressures, the Left Rear and the Right Rear corner pressures and all four corner pressures *combined*. Therefore there was no benefit in adjusting any of the corner pressures since the optimum setting would depend on *all four* of the corner pressure settings. Making an adjustment to any of the corner pressures would affect the others.

9.5 Summary of Analysis

As shown in appendix8, the three combinations of corner pressures shown to have an effect on *all* of the flange lengths were Left Rear and Right Rear, Left Front and Left Rear and all four corner pressures combined. This was reflected by the Yates analysis for each edge of the part. For the Left Edge, the difference between the sums of insignificant combinations was less than 11% of the difference between the sums of significant combinations (those mentioned above). For the Side Edge, the same figure was less than 8%, for the Left Edge it was less than 6% and for the Front Edge, less than 2%. This demonstrated that the effects of the combinations of inputs mentioned above had a far greater influence than any other combination or combinations.

9.6 Conclusions

The conclusions drawn from this set of experiments were that there is no advantage to be gained by adjusting one two or three corner pressures. The reason is that the same trend, that is all four corner pressures having a combined effect, is evident on all sides of the part with very similar strength (11, 8, 6 and 2 percent). Therefore, in order to have a controlled influence on the part, *all four* corner pressures would need to be adjusted together, in other words, changing one corner pressure *could* change any of the other three. To do this in a controlled fashion, much more data would have to be obtained in order to understand which combinations of all four corner pressures yields the best overall result. The best overall, because it is possible that a combination giving the best result for one side of the part will cause another side of the part to create a short flange.

CHAPTER 10

THE WAY FORWARD

10.1 Introduction

There is only so much that could be achieved in a two year period, particularly in light of the fact that the project had an industrial focus meaning that not only academic but also industrial parties had to be satisfied. Because of this, in the course of study, many other questions had been raised and many other avenues of research left unchallenged. It is important that these issues be pursued in any further research in this area particularly in research projects such as this if the overall body of knowledge of the stamping process is to continue to improve.

10.2 Optimisation of Response Surfaces

The method used in chapter8 to improve part quality involved the generation of four control surfaces and from them, derivation of a final region or window of operation which is deemed to be safe. It is envisaged that the same methodology used to determine the safe regions of the control surfaces be used generically throughout the press shop. The reason for this is that it allows for a more methodical rather than haphazard approach to solving press shop problems. In its initial stage, it involves determining statistically which variables are influential in the process and then determining which combination of these variables results in the most favourable output.

10.3 Feedback control of Binder Pressure

One of the points discovered during the course of study was that one of the most important parameters in press forming is friction. More importantly, it is the actual binder pressure applied to the blank which determines the friction force acting between the blank and the die faces. One naturally asks the question - what controls the binder pressure? There are many factors, however, the factor which has the greatest impact is the shut height, this may be readily appreciated by studying press dynamics and the basic design of a press. Other factors such as corner pressures and die shims also effect the binder pressure however the way in which they do this is by altering the gap between the upper and lower tool - a distance often referred to as the blankholder gap. This is really the same as raising or lowering the slide (a change in shut height) although the use of the latter enables one to make a much less coarse adjustment which may be thought of as "fine tuning".

It would be advantageous if one were able to construct a feedback loop incorporating the blankholder gap and or tonnage variation over time with the shut height mechanism. Then, should an insufficient amount of pressure be experienced - correction would be achieved by adjusting the slide either up or down thereby adjusting the shut height and creating favourable friction conditions, this has been well documented [39],[41],[77],[122],[123]. In some instances, the amount of adjustment would be so fine that adjusting the shut height would be too dramatic. However, between production runs, the feedback system would save time during die set by reducing the time it takes to get the right amount of blankholder gap.

10.4 In Die Sensing

As previously mentioned, one of the most important factors affecting the stamping process is friction. In line with this is force since the value of friction will be affected by amongst other things, clamping force. This has led to the belief that if the "forming pressure" or contact force could be determined and then re-produced at crucial locations in a die, then many of the mysteries of press forming operations could be solved. This is because there are many factors which all add up in one way or another to generate an amount of contact pressure on a panel. The theory is that if this amount of force can be re-produced with confidence each time a part is formed, then regardless of what the other variable settings are - one should be producing a satisfactory part. In reality, one will still have to understand the interactions of the input variables on the process - this leaves a lot of scope for in plant DoE work to develop this understanding, however once this understanding is developed, a lot of the guesswork will be taken out of die setting by using DoE information and in die sensors in parallel. In die sensing generally consists of placing industrial type strain gages onto specific areas of concern on a die. These gages are then connected to instrumentation which allows one to observe the signal of the strain gauge throughout the stroke of the press. An acceptable value for the signal will correspond to a satisfactory part and this is generally established as the "benchmark" for future production.

10.5 FE Modelling using commercial packages

The use of Computer Modelling using commercial packages such as ABAQAS has great potential in saving time in tryout. The potential savings may not be apparent at first glance, however, upon closer scrutiny, the potential savings are huge. At present, there is a rather large amount of time required from design to finished part in stamping. This means that research personnel who are investigating structural changes do not get the opportunity to investigate very many options. This is because they have to wait a long time before an idea or theory is proved out in die building and the tryout process. If on the other hand, reliable computer simulations were available, many more options and ideas could be considered and tested. Not only does this save great amounts of money during die tryout, it also allows for a more competitive product since more improvements may be incorporated in the same amount of time.

This includes tryout time allotted for DoE which may by easily carried out on a model once sufficient effort has been injected into the model allowing it to sufficiently re-produce reality. This allows one to "make changes" without affecting the plant or production in any way with the result that "the information is there if you want to use it". If no action is taken, nobody has really lost anything since no production or die building time was required. Besides the DoE aspect of modelling, a computer model which is representative of the process and has a reasonably short processing time, allows one to do the job of the toolmaker and die designer in that the die may be modified in any way one chooses - the relative effects observed with no loss to the plant whatsoever. The difficulties at this stage lie in the way the computer models currently operate compared to an actual press.

In some FE modelling for example, one must assign a value of the co-efficient of friction to known areas of the blankholder and/or blank whereas in real life (this was the case with this project), the actual value for the co-efficient of friction is unknown and will never be uniform over "certain areas". Also, in a press/die/blank system, friction forces and clamping force is achieved by adjusting the relative displacement of the punch and slide causing a certain amount of force to be generated at the punch and slide respectively. The other finer methods of adjustment such as corner pressure and die shims basically act to change this force slightly. Also, in an FE model, the blankholder may be displaced by a certain amount whilst the resultant force (tonnage) is measured or vice versa.

Nevertheless, DoE may assist in determining the relationship between tonnage, corner pressure and blankholder gap in order to determine which is the most effective method of operating the model. This contributes towards building an understanding which begins to bridge the gap between the model and reality.

10.6 Tonnage Measurement

Currently, tonnage is measured by placing strain gauges on the press columns. These are calibrated by placing load cells underneath the press ram with no die in the die space. Despite the calibration procedure, the validity of the amount of force measured by these gauges is an ongoing point of conjecture due to their location (offset to the point of load application). One of the disadvantages of measuring tonnage in this way is demonstrated simply by the fact that one is using a single device to measure two separate entities. Put differently, the output of a chart recorder connected to the instrumentation associated with this type of system is simply a single force versus time graph, the force corresponding initially to the blankholder force, then the punch force and finally the blankholder force. This leads to confusion as to when the force represented on the graph refers to punch force or blankholder force. The manufacturer of the strain gages used in the in plant experimentation claimed that there were techniques to differentiate between the two, however, at the time, in plant systems did not have the capability to do this with the existing software. Another disadvantage of measuring tonnage by this means is the inaccuracies which arise when the press is cycled at higher speeds. Taken to the extreme case for example, transducers mounted in the columns of a press operating at 180 strokes per minute will record nothing more than vibrations of the press frame.

Transducers mounted in the columns of presses operating at low speeds such as 12 strokes per minute for example are representative of the forces acting within a die set, however, there does not appear to be a method of differentiating between a 'high' cycle and a 'low' cycle press.

It was possible to download data from the tonnage monitors used in the Stamping Plant into a computer. This data consists of 10 values of tonnage previously described. Data was measured continually and it was possible to observe the tonnage values on monitors located on the exterior of the particular press in question. Values were recorded on computer on a time basis allowing one to measure tonnage values for each successive hit.

When running a Finite Element model, it is possible to operate either in force control or position control. This means that either the displacement is specified as part of the system constraints and tonnage is calculated by the model or vice versa. Therefore, it would be advantageous to know exactly how much tonnage is being developed on both the blankholder and the punch and/or other areas within the die (in die sensing). Apart from this, measurement of tonnage allows for other benefits especially when tonnage is measured throughout the stroke of the press cycle for both the punch and the blankholder simultaneously. These benefits include determining the condition of the press and die components - information which is important for maintenance and toolmakers enabling one to maintain the tools and press in a satisfactory condition.

A proposal was put forward allowing one to measure tonnage for both the punch and the blankholder separately in the form of what was called a tonnage plate [120]. The purpose of this plate was to generate a two dimensional profile of tonnage versus time or a 'tonnage footprint' for each individual hit over a whole production run. A common way to measure force in industrial applications is to use strain gage based transducers. A strain gage based transducer consists simply of an element, commonly known as the spring element which has strain gages mounted on it and is usually concealed in a housing. When the spring element is deformed under load, the strain gages detect the deformation and the signal being emitted by the strain gage varies, the degree of variation corresponding to a particular load pre-determined during calibration. In order to reduce costs and simplify the design, the load cell or transducer was to be one and the same as the spring element.

Our intention was to mount a series of these spring elements in between two plates and to further mount this unit in between the blankholder (ring) and the upper ram (outer slide) as shown in Figure18.

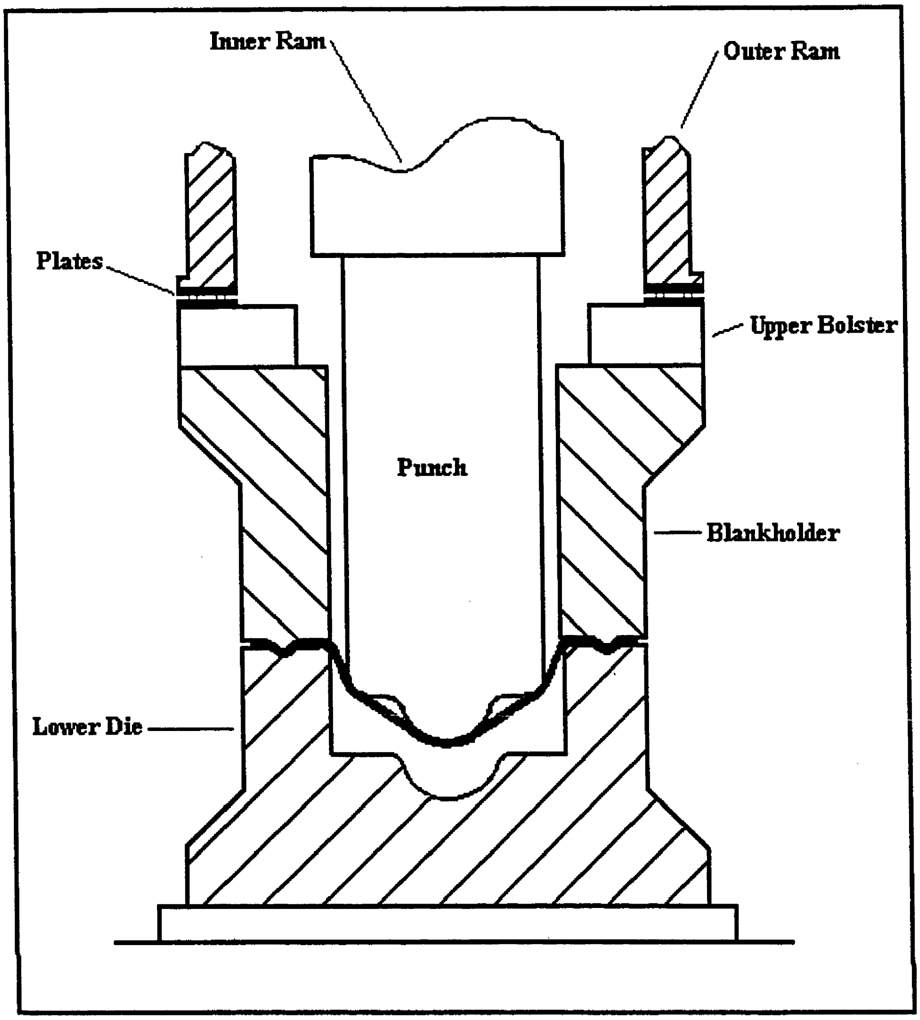


Figure18 - Tonnage Plate Location

Thus it would be possible to obtain signals corresponding to the blankholder over the whole perimeter and not just in the four corners for each hit for as long as the system constraints allow. It was initially intended to manufacture two such units with the second unit being mounted in-between the punch and the inner ram. This was rejected on the grounds that it would be too difficult to feed instrumentation wires out from the punch in-between the inner and outer ram.

It was also intended to log the signals produced by each of the elements using a data logging facility in order to draw comparisons between tonnage readings. It was intended to use instrumentation which would enable calibration of the strain gage configuration (wheatstone bridge), compensate for thermally induced errors and allow the setting of gage factors. For more detail on the method for measuring tonnage, refer to the tonnage plate work [120].

Other methods which might be employed to measure tonnage more accurately include a relatively cheap item known as pressure sensitive film. It consists basically of a thin membrane which when deformed creates a colour distribution, the different colours corresponding to different levels of stress or force. The colours are interpreted by an optical device developed by the manufacturer of the film so there is no human error in determining the amount of force applied to the film [6].

This film could be applied either directly to the die face or to the setting blocks. If applying the film to the die face was possible, then the exact amount of force applied to the binder would be known. Alternately, should the film interfere with the forming process, it could be placed on the setting blocks. In this case, the amount of force which is transferred to the setting blocks would be known. This could be subtracted from the tonnage monitor readings to give a better idea as how much force is actually transmitted to the die face itself.

In order to make FE modelling more useful, it is necessary to gain a quantitative understanding of the amount of force and its distribution at least on the blankholder, to this end, force measurement should be high on the list of priorities for future research into sheet metal forming.

10.7 Blankholder Gap Measurement

As with tonnage, from a modelling point of view, it would be very useful to be able to measure the relative displacement between the upper and lower tool of a die set approaching and at B.D.C. This is because blankholder gap is an input to the computer model and in reality affects the amount of friction acting within a die set. Another benefit is that it would allow for quicker die set times simply because the blankholder gap for a good part may be determined and reproduced using these devices regardless of which press line the part is running in. Also, the state of levelness of the ram may be also readily determined if four transducers are used, one on each corner of the ram.

Many problems forming a part in the press shop are attributed to the out of levelness condition of the ram. An out of level ram is a serious impairment in a press shop, potentially causing serious difficulties [43]. This is because at the beginning of the life of a Die, it is cast and bedded to produce a satisfactory part. However, if the die is placed in a press with an out of level ram, then it is quite possible that the part will split, wrinkle or develop some other kind of defect. If there is no proof that the ram is in an out of level condition, then it is the toolmakers job to modify the die using grinding tools or shims in order to obtain a satisfactory part. Now consider the case that the same "modified" die is put into a different press line, either with a level ram press or even worse than before, a ram which is out of level at a different angle (which has happened), the die will once more have to be modified and so it goes on. The out of level condition of a ram is a serious impediment to making a good part, causing unnecessary die wear and adversely affecting press performance which can in turn come back to affect the part in a different way - a vicious circle.

At present there is no practical way of determining the levelness condition of the ram *during* production. There are several devices which could be used for this task. Some possibilities include, linear transducers, dial gauges and linear scales [11],[12]. These devices usually used in industrial gauging could easily be adapted to the press shop environment. They would be delicate however they are accurate and precise enough to yield acceptable data.

With regards to the Blankholder gap, it is recommended that linear transducers be installed on each corner of the exterior of a die set should costs permit. The physical set-up would dictate that one part of the transducer (the magnetic head) be connected to the upper part of the die while the other part of the transducer (the linear track) be connected to the corresponding press column. This set-up would enable users to measure the displacement of the upper die relative to the press structure, allowing one to detect variation.

10.8 Flexible Tooling

An analogy was drawn earlier about the Stamping Process where it was described as being similar to the common bicycle lock and that the correct combination of variables leads to satisfactory operation. This is probably true of most industrial processes though in stamping, the amount of variables is very large. Therefore, it would be of great benefit if one was able to reduce the amount of variables. Fortunately there exists technology which does not have anywhere near as many variables as traditional stamping. This technology is flexible tooling.

In the conventional stamping scenario, it is necessary to use Mechanical Presses in order to achieve the high production rates necessary to make the Stamping of sheet metal profitable. A mechanical press is in simple terms a reciprocating device, it stands there in the shop pounding dies, day in, day out. It is no wonder that the die surface becomes worn, that the gibs become worn, leading to an out of level ram, that the slide adjustment mechanism may slip further aggravating the problem. It is no wonder that it is so difficult to control the flow of metal into a die simply by clamping it about its perimeter and effectively transferring the load to the four corners of the blank. It is no wonder that the headache only grows when dies are incorrectly stored, and when further variables such as lubricant, metal specifications and ambient temperature are brought into the equation.

With the existing technology, there is definitely scope for improvement, one may conduct copious amounts of experiments and obtain enough data to determine or specify a "safe" region of operation. Yet it is the authors belief that this will only address the problem to a certain degree. It certainly will not make the process flawless and there will definitely be circumstances of unexplained splits or wrinkles. The understanding of these can be greatly enhanced with the aid of a good computer model, particularly if it is generated using real time data.

However, to obtain the degree of quality being demanded of Auto Manufacturers at present, it is the authors belief that the technology being used to form the product must be upgraded. The standard to which skin panels must be produced can no longer be controlled by the press parameters and it is no wonder if one considers the physical process as described earlier. It is virtually impossible to eliminate a very small defect such as a low mark in a panel by making adjustments on the press. These type of defects are caused either by minute particles on the die surface which is a matter of die cleanliness, or by cumulative strain and release of residual stress. How can these types of problems be practically avoided in the press shop where dust and dirt (we are talking about particles of very small magnitude) are continually being distributed everywhere? This method of stamping has generated the need for the Artisan, the person who actually gets inside a die while it is in the press and makes the modifications necessary to create an acceptable part.

To address these problems, it is necessary to look into the area of flexible tooling. This is a process where panels may be drawn and in most cases trimmed without many of the traditional press shop problems, with reduced cost in many areas and with more simplicity. Instead of utilising an upper and lower tool, both of which have traditionally been metal, only a lower tool is necessary. Deformation is achieved by forcing a rubber diaphragm over the blank and forcing it to conform to the profile of the lower tool with high pressure fluid. Traditionally, this has been the downside, hydraulics are involved leading to slower cycle times, times which may or may not compete favourably with a traditional mechanical press. Despite this, it has been very common in press shops as a die tryout tool [51].

There is a real process being used by large auto manufacturers such as SAAB [52], which needs half as much tooling (big savings), very little tryout time (big savings), virtually no set-up time (big savings), virtually no unexpected scrap (considerable savings) and considerably lower maintenance and die repair (big savings). Besides this, part quality is excellent, particularly with skin panels where the die may be designed such that the exterior surface only makes contact with the rubber diaphragm. The only downside at the moment is that it is too slow for high volume production. However, it is possible to make significant savings in low to medium volumes of production. The Toyota Flexible Press System is well documented and demonstrates the ability of flexible forming to compete favourably over conventional press lines. In this particular case, eleven major components including the hood, door (both inner and outer), fenders and quarter panels were manufactured using a hybrid system known as hydromechanical forming leading to a reduction in die costs of 65% [87]. Hydromechanical forming is almost identical to flexible forming only in this case, special dies are manufactured which consist of the conventional upper tool but have a liquid pressure system in the lower half of the die instead of a lower tool. Also, a binder is still utilised which means that these special dies may be used in conventional double action mechanical presses.

The result has been the above mentioned advantages. Reduced "in process" problems, especially those causing skin finish panels to be rejected, reduced die set times and much reduced hit to hit times. It would be a worthwhile exercise to evaluate the cost of implementing a similar system in future projects of this nature comparing the volumes required in this operation with those of the production of Sera [87].

10.9 Improved processing time and FE Modelling Capability

Improvements in computer technology, particularly in processing time are legitimate avenues of research in sheet metal forming. At present, it is very rare to see a complete model of the whole press/die/blank system. The reasons for this are varied however one definite reason is the lack of resources and computing power to generate a model of such complexity. Usually, the blank and die surfaces are modelled and press frames themselves have been modelled, however not from the point of view of stamping simulations. In the past, modelling of the press frame has been carried out to optimise the dimensions of the structural members of a press frame.

The reason why modelling of the system would be useful is because the model would be a *true* simulation. At present, it is possible to simulate quite closely the die surface and the blank and this has indeed been done quite successfully. The trouble with this however is that the press operator does not operate a press by entering a co-efficient of friction into a keyboard nor does he specify an exact displacement of the press ram or an amount of force to be applied to a binder. He/She has no such luxury. In a drawing operation, the operator will have 4 to 5 variables which he/she may change. These are the shut height (which in truth is the relative displacement of the press ram though not to the degree of accuracy which one would specify in a FE model), the blank position, the corner pressures, the lubrication and possibly pressure of cylinders within some complex dies which control additional binder pressures. It is very difficult to relate the information, both the input and output information used in a conventional FE model to the settings which a press operator uses on the shop floor. Besides the differences between the way in which a model is constrained and the way a real press operates, there is the idealised operating conditions usually inherent in an FE model.

An FE model for instance will not usually take into account the flexibility of both the upper and lower tool. It cannot simulate the use of setting blocks nor the use of shims on a setting block. It cannot be set to run such that the upper tool is slightly tilted which may be the case in a press shop when the press ram is out of level.

A computer model will not take into account the change in tonnage developed caused by worn press components such as play in the press crown or worn press gibs nor does it take into account the extra resistance offered to the ram by counterbalance cylinders or the effect of changing corner pressures on a press ram which in effect cause more force to be applied by the binder in some areas compared with others.

And so therefore, FE models despite the vast improvements made in the last couple of years are still very primitive when viewed in this light. It is therefore necessary to try to model the whole system. In this way, the guesswork and complicated relationships joining a model with reality do not have to be generated which would require copious amounts of DoE on one part alone, the answers from which could not be used generically.

10.10 Modelling Friction

In keeping with the issues raised in this document, in particular, if the points raised in 10.9 are to be successful, more information needs to be obtained about how friction is interacting with the process. Often dubbed the impossible task, friction has more often than not been accepted as a "too hard" subject and a hence the subject of dubious approximation. This is still the case however, if progress is to be made in simulation of sheet metal forming, the problem has to be tackled. Granted, it is going to be a grievous and painstaking task yet the problem needs to be attacked with fervour and zeal if it is ever going to be resolved. One possibility is that for a particular die in question, sophisticated strip draw tests be developed which only seek to simulate friction at certain locations on the die face. This information should then be gathered and used collectively to specify the co-efficient of friction at the corresponding locations in the die mesh eventually yielding a complex die mesh so sophisticated that it contains many separate regions all with differing co-efficients of friction.

10.11 Research of Sheet Metal Production

This thesis describes a method of attacking the problems in the process of sheet metal forming. It involves process understanding followed by measurement followed by experimentation. If future research into sheet metal forming is to be successful via projects such as these, an approach similar to the one taken for this project should be taken in the manufacture of steel coils used by stamping plants. This would be of great benefit to sheet metal forming researchers. The reason for this is that the manufacture of steel suffers the same predjudices and haphazard approach as stamping does. Solving the problems in stamping may only be part way to an eventual solution. The manufacture of metal must be properly understood, made repeatable and optimised if stamping of sheet metal is to enjoy the repeatability which so many people, both managers and workers alike so desire.

10.12 Die Wear monitoring scheme

No process is ever perfect and stamping of sheet metal is by no means perfect. A contributing factor to this is that dies simply wear. As they wear, their profiles naturally change and a die design which is insufficiently robust could cause serious problems after a relatively short amount of use. When a die is worn, the toolmaker will begin his process of griding and filing or replacement of metal to try to rectify the situation. This, as previously mentioned, can be somewhat of a hit and miss process and therefore, it would be suitable to have the surface of a die scanned and recorded such that there is some tolerance in between which an acceptable part is produced. Should this tolerance be violated i.e by excessive wear then the die should not be used until it is repaired. A die monitoring program would mean that dies are checked on a regular basis to determine whether or not the important geometries lie within the specified tolerance. In fact there have been attempts made using FEM to optimise draw die profile [21]. It is this sort of work which needs to be pursued with perhaps less theoretical emphasis in the press shop.

CHAPTER 11

OVERALL CONCLUSIONS

This thesis did not follow the traditional lines of sheet metal forming research. It attempted to strike a balance between theory and practice, to be pragmatic enough to have a real impact on the area of endeavour and yet be theoretical enough to provide a generic framework which may be built upon by further research. This was to be achieved by spending long periods of time in the industrial environment and under these circumstances, it is difficult to satisfy both the industrial and academic parties. Nevertheless, real improvements to the process and real understanding of the process was achieved opening the way for further improvements.

This thesis shows that factorial experimentation techniques using statistical methods may be applied to a manufacturing environment to create consistency and hence improve efficiency. The experimentation was carried out in an industrial environment on a real production part and real benefits were achieved. Scrap levels were considerably reduced such that the part as it now runs does not appear as a high scrap item where it once held sixth place. The thesis also outlines a basic methodology consisting of process understanding, characterisation, measurement and finally process optimisation. The technique itself is relatively simple and cost effective meaning it can be applied to virtually any manufacturing process.

However, these techniques are generally more powerful when employed to tackle easier problems, there are dies and processes in todays press shops where it would be difficult to apply this methodology with such effectiveness. In the initial stages of process improvement, this methodology is almost essential as it generates the basic knowledge needed to operate the process efficiently. To make the giant leaps forward that are so desired in stamping operations with todays technology (mechanical presses), real progress in FE modelling needs to take place. FE modelling is an excellent method of predicting trends , in this area it is exceptionally strong. However, to fulfill the potential of FE modelling, much improvement is required. The two most crucial areas are modelling friction and simulating *the process* as closely as possible. It is not sufficient to simulate just the press or just the tools, it is necessary to simulate the *system*.

APPENDIX1

Experiment No.1					
Inputs			Setting		
a) Shut Height			62.537	in	
b) Lubricant			Roll Coater		
c) Blank Position			# 1		
d) Corner Pressure			304	kPa	
Outputs		Specimen No.1	Specimen No.2	Specimen No.3	
a) Draw-in to Side Edge		120.5	120.5	122.5	mm
b) Draw-in to Front Edge		127	130	127	mm
c) Strain Distribution					
	A4.5	0.91	0.88	0.9	mm
	C4.5	0.92	0.91	0.91	mm
	E4.5	0.92	0.92	0.92	mm
	G4.5	0.94	0.92	0.92	mm
d) Peak Punch Tonnage		621	620	620	tons
e) Peak Blankholder Tonnage		195	197	196	tons

Table1

Experiment No. 2					
Inputs			Setting		
a) Shut Height			62.55	in	
b) Lubricant			Roll Coater		
c) Blank Position			# 1		
d) Corner Pressure			304	kPa	
Outputs		Specimen No.1	Specimen No.2	Specimen No.3	
a) Draw-in to Side Edge		113.5	112	115	mm
b) Draw-in to Front Edge		128	129.5	131	mm
c) Strain Distribution					
	A4.5	0.9	0.9	0.88	mm
	C4.5	0.91	0.91	0.91	mm
	E4.5	0.9	0.91	0.92	mm
	G4.5	0.92	0.92	0.92	mm
d) Peak Punch Tonnage		616	619	614	tons
e) Peak Blankholder Tonnage		159	156	154	tons

Table2

Experiment No.3					
Inputs			Setting		
a) Shut Height			62.55	in	
b) Lubricant			Roll Coater		
c) Blank Position			# 1		
d) Corner Pressure			405	kPa	
Outputs		Specimen No.1	Specimen No.2	Specimen No.3	
a) Draw-in to Side Edge		109.5	114	118	mm
b) Draw-in to Front Edge		127.5	133.5	128	mm
c) Strain Distribution					
	A4.5	0.91	0.88	0.9	mm
	C4.5	0.94	0.91	0.94	mm
	E4.5	0.92	0.91	0.9	mm
	G4.5	0.92	0.92	0.92	mm
d) Peak Punch Tonnage		615	615	619	tons
e) Peak Blankholder Tonnage		161	159	162	tons

Table3

Experiment No. 4					
Inputs			Setting		
a) Shut Height			62.537	in	
b) Lubricant			Roll Coater		
c) Blank Position			# 1		
d) Corner Pressure			405	kPa	
Outputs		Specimen No.1	Specimen No.2	Specimen No.3	
a) Draw-in to Side Edge		117	112	115	mm
b) Draw-in to Front Edge		124.5	129.5	131	mm
c) Strain Distribution					
	A4.5	0.9	0.88	0.88	mm
	C4.5	0.9	0.91	0.91	mm
	E4.5	0.9	0.91	0.9	mm
	G4.5	0.92	0.92	0.92	mm
d) Peak Punch Tonnage		626	623	619	tons
e) Peak Blankholder Tonnage		200	200	204	tons

Table4

Experiment No.5					
Inputs			Setting		
a) Shut Height			62.55	in	
b) Lubricant			Roll Coater		
c) Blank Position			# 2		
d) Corner Pressure			304	kPa	
Outputs		Specimen No.1	Specimen No.2	Specimen No.3	
a) Draw-in to Side Edge		125.5	130	126.5	mm
b) Draw-in to Front Edge		133	130.5	132	mm
c) Strain Distribution					
	A4.5	0.9	0.88	0.88	mm
	C4.5	0.91	0.92	0.91	mm
	E4.5	0.91	0.9	0.92	mm
	G4.5	0.92	0.91	0.92	mm
d) Peak Punch Tonnage		616	616	618	tons
e) Peak Blankholder Tonnage		152	154	154	tons

Table5

Experiment No. 6					
Inputs			Setting		
a) Shut Height			62.537	in	
b) Lubricant			Roll Coater		
c) Blank Position			# 2		
d) Corner Pressure			304	kPa	
Outputs		Specimen No.1	Specimen No.2	Specimen No.3	
a) Draw-in to Side Edge		140	137	136.5	mm
b) Draw-in to Front Edge		130	130	131.5	mm
c) Strain Distribution					
	A4.5	0.91	0.9	0.88	mm
	C4.5	0.91	0.94	0.94	mm
	E4.5	0.9	0.9	0.9	mm
	G4.5	0.92	0.94	0.94	mm
d) Peak Punch Tonnage		619	619	623	tons
e) Peak Blankholder Tonnage		191	191	195	tons

Table6

Experiment No.7					
Inputs			Setting		
a) Shut Height			62.55	in	
b) Lubricant			Roll Coater		
c) Blank Position			# 2		
d) Corner Pressure			405	kPa	
Outputs		Specimen No.1	Specimen No.2	Specimen No.3	
a) Draw-in to Side Edge		123.5	123.5	121.5	mm
b) Draw-in to Front Edge		130.5	131	130	mm
c) Strain Distribution					
	A4.5	0.88	0.9	0.9	mm
	C4.5	0.92	0.91	0.9	mm
	E4.5	0.9	0.9	0.9	mm
	G4.5	0.92	0.92	0.92	mm
d) Peak Punch Tonnage		615	615	615	tons
e) Peak Blankholder Tonnage		161	160	159	tons

Table7

Experiment No. 8					
Inputs			Setting		
a) Shut Height			62.537	in	
b) Lubricant			Roll Coater		
c) Blank Position			# 2		
d) Corner Pressure			405	kPa	
Outputs		Specimen No.1	Specimen No.2	Specimen No.3	
a) Draw-in to Side Edge		127.5	133	126.5	mm
b) Draw-in to Front Edge		129.5	131	131	mm
c) Strain Distribution					
	A4.5	0.88	0.88	0.88	mm
	C4.5	0.92	0.91	0.92	mm
	E4.5	0.92	0.9	0.91	mm
	G4.5	0.94	0.92	0.92	mm
d) Peak Punch Tonnage		625	623	623	tons
e) Peak Blankholder Tonnage		198	199	199	tons

Table8

Experiment No.9					
Inputs			Setting		
a) Shut Height			62.55	in	
b) Lubricant			Mill Oil		
c) Blank Position			# 1		
d) Corner Pressure			304	kPa	
Outputs		Specimen No.1	Specimen No.2	Specimen No.3	
a) Draw-in to Side Edge					mm
b) Draw-in to Front Edge					mm
c) Strain Distribution					
	A4.5				mm
	C4.5				mm
	E4.5				mm
	G4.5				mm
d) Peak Punch Tonnage					tons
e) Peak Blankholder Tonnage					tons

Table9

Experiment No. 10					
Inputs			Setting		
a) Shut Height			62.537	in	
b) Lubricant			Mill Oil		
c) Blank Position			# 1		
d) Corner Pressure			304	kPa	
Outputs		Specimen No.1	Specimen No.2	Specimen No.3	
a) Draw-in to Side Edge					mm
b) Draw-in to Front Edge					mm
c) Strain Distribution					
	A4.5				mm
	C4.5				mm
	E4.5				mm
	G4.5				mm
d) Peak Punch Tonnage					tons
e) Peak Blankholder Tonnage					tons

Table10

Experiment No.11					
Inputs			Setting		
a) Shut Height			62.55	in	
b) Lubricant			Mill Oil		
c) Blank Position			# 1		
d) Corner Pressure			405	kPa	
Outputs		Specimen No.1	Specimen No.2	Specimen No.3	
a) Draw-in to Side Edge					mm
b) Draw-in to Front Edge					mm
c) Strain Distribution					
	A4.5				mm
	C4.5				mm
	E4.5				mm
	G4.5				mm
d) Peak Punch Tonnage					tons
e) Peak Blankholder Tonnage					tons

Table11

Experiment No. 12					
Inputs			Setting		
a) Shut Height			62.537	in	
b) Lubricant			Mill Oil		
c) Blank Position			# 1		
d) Corner Pressure			405	kPa	
Outputs		Specimen No.1	Specimen No.2	Specimen No.3	
a) Draw-in to Side Edge					mm
b) Draw-in to Front Edge					mm
c) Strain Distribution					
	A4.5				mm
	C4.5				mm
	E4.5				mm
	G4.5				mm
d) Peak Punch Tonnage					tons
e) Peak Blankholder Tonnage					tons

Table12

Experiment No.13					
Inputs			Setting		
a) Shut Height			62.55	in	
b) Lubricant			Mill Oil		
c) Blank Position			# 2		
d) Corner Pressure			304	kPa	
Outputs		Specimen No.1	Specimen No.2	Specimen No.3	
a) Draw-in to Side Edge		off scale			mm
b) Draw-in to Front Edge		119.5			mm
c) Strain Distribution					
	A4.5	0.76			mm
	C4.5	0.92			mm
	E4.5	0.86			mm
	G4.5	0.88			mm
d) Peak Punch Tonnage		605			tons
e) Peak Blankholder Tonnage		147			tons

Table13

Experiment No. 14					
Inputs			Setting		
a) Shut Height			62.537	in	
b) Lubricant			Mill Oil		
c) Blank Position			# 2		
d) Corner Pressure			304	kPa	
Outputs		Specimen No.1	Specimen No.2	Specimen No.3	
a) Draw-in to Side Edge		off scale			mm
b) Draw-in to Front Edge		130			mm
c) Strain Distribution					
	A4.5	0.77			mm
	C4.5	0.77			mm
	E4.5	N/A			mm
	G4.5	N/A			mm
d) Peak Punch Tonnage		615			tons
e) Peak Blankholder Tonnage		190			tons

Table14

Experiment No.15					
Inputs			Setting		
a) Shut Height			62.55	in	
b) Lubricant			Mill Oil		
c) Blank Position			# 2		
d) Corner Pressure			405	kPa	
Outputs		Specimen No.1	Specimen No.2	Specimen No.3	
a) Draw-in to Side Edge					mm
b) Draw-in to Front Edge					mm
c) Strain Distribution					
	A4.5				mm
	C4.5				mm
	E4.5				mm
	G4.5				mm
d) Peak Punch Tonnage					tons
e) Peak Blankholder Tonnage					tons

Table15

Experiment No. 16					
Inputs			Setting		
a) Shut Height			62.537	in	
b) Lubricant			Mill Oil		
c) Blank Position			# 2		
d) Corner Pressure			405	kPa	
Outputs		Specimen No.1	Specimen No.2	Specimen No.3	
a) Draw-in to Side Edge					mm
b) Draw-in to Front Edge					mm
c) Strain Distribution					
	A4.5				mm
	C4.5				mm
	E4.5				mm
	G4.5				mm
d) Peak Punch Tonnage					tons
e) Peak Blankholder Tonnage					tons

Table16

APPENDIX2

Influence of factors on Flange Length on Side Edge								
						Columns (c)		
				Groups (g)		Shut Height		
						c1	c2	
						62.537	62.55	
		A1		Blank Position		120.5	113.5	
		Corner Pressure		# 1		120.5	112	
		304 kPa		B1		122.5	115	
				Blank Position		140	125.5	
				# 2		137	130	
				B2		136.6	126.5	
Rows (r)								
		A2		Blank Position		117	109.5	
		Corner Pressure		# 1		116.5	114	
		405 kPa		B1		120	118	
				Blank Position		127.5	123.5	
				# 2		133	123.5	
				B2		126.5	121.5	
c	n	r	g	N	T			
2	3	2	2	24	2950.1			
SS(c)	SS(r)	SS(g)	SS(cr)	SS(cg)	SS(rg)	SS(crg)	SS(total	SS(resd)
301.75	100.45	963.93	24.2	9.5004	40.3	0.1838	1536.1	-1440
				MSR min for significance				
SS	DF	MS	MSR	90%	95%	97.50%		
301.75	1	301.75	16.27	4.54	7.71	10	Shut Height	
100.45	1	100.45	5.4162	4.54	7.71	10	Corner Pressures	
963.93	1	963.93	51.975	4.54	7.71	10	Blank Position	
24.2	1	24.2	1.3049	4.54	7.71	10	Sht Ht & Cnr Prs	
9.5004	1	9.5004	0.5123	4.54	7.71	10	Sht Ht & Blnk Psn	
40.3	1	40.3	2.173	4.54	7.71	10	Cnr Prs & Bnk Pn	
0.1838	1	0.1838	0.0099	4.54	7.71	10	Cp & Bp & Sh	
74.185	4	18.546						

Table1

Influence of factors on Flange Length on Front Edge								
						Columns (c)		
				Groups (g)		Shut Height		
						c1	c2	
						62.537	62.55	
		A1		Blank Position		127	128	
		Corner Pressure		# 1		130	129.5	
		304 kPa		B1		127	131	
				Blank Position		130	133	
				# 2		130	130.5	
				B2		131.5	132	
Rows (r)								
		A2		Blank Position		124.5	127.5	
		Corner Pressure		# 1		126.5	133.5	
		405 kPa		B1		127.5	128	
				Blank Position		129.5	130.5	
				# 2		131	131	
				B2		131	130	
c	n	r	g	N	T			
2	3	2	2	24	2950.1			
SS(c)	SS(r)	SS(g)	SS(cr)	SS(cg)	SS(rg)	SS(crg)	SS(total	SS(resd)
15.042	3.375	37.5	0.1667	5.0417	0.0417	4.1667	109.33	-65.33
				MSR min for significance				
SS	DF	MS	MSR	90%	95%	97.50%		
15.042	1	15.042	6.3894	4.54	7.71	10	Shut Height	
3.375	1	3.375	1.4336	4.54	7.71	10	Corner Pressures	
37.5	1	37.5	15.929	4.54	7.71	10	Blank Position	
0.1667	1	0.1667	0.0708	4.54	7.71	10	Sht Ht & Cnr Prs	
5.0417	1	5.0417	2.1416	4.54	7.71	10	Sht Ht & Blnk Psn	
0.0417	1	0.0417	0.0177	4.54	7.71	10	Cnr Prs & Bnk Pn	
4.1667	1	4.1667	1.7699	4.54	7.71	10	Cp & Bp & Sh	
9.4167	4	2.3542						

Table2

Influence of factors on Wall Thickness @ A4.5								
						Columns (c)		
				Groups (g)		Shut Height		
						c1	c2	
						62.537	62.55	
		A1		Blank Position		0.91	0.9	
		Corner Pressure		# 1		0.88	0.9	
		304 kPa		B1		0.9	0.88	
				Blank Position		0.91	0.9	
				# 2		0.9	0.88	
				B2		0.88	0.88	
Rows (r)								
		A2		Blank Position		0.9	0.91	
		Corner Pressure		# 1		0.88	0.88	
		405 kPa		B1		0.88	0.9	
				Blank Position		0.88	0.88	
				# 2		0.88	0.9	
				B2		0.88	0.9	
c	n	r	g	N	T			
2	3	2	2	24	2950.1			
SS(c)	SS(r)	SS(g)	SS(cr)	SS(cg)	SS(rg)	SS(crg)	SS(total	SS(resd)
# # # #	0.0001	0.0001	0.0005	# # # #	# # # #	# # # #	0.0033	-8E-04
				MSR min for significance				
SS	DF	MS	MSR	90%	95%	97.50%		
4E-05	1	4E-05	0.2727	4.54	7.71	10	Shut Height	
0.0001	1	0.0001	0.7564	4.54	7.71	10	Corner Pressures	
0.0001	1	0.0001	0.7564	4.54	7.71	10	Blank Position	
0.0005	1	0.0005	3.6655	4.54	7.71	10	Sht Ht & Cnr Prs	
4E-06	1	4E-06	0.0303	4.54	7.71	10	Sht Ht & Blnk Psn	
4E-06	1	4E-06	0.0303	4.54	7.71	10	Cnr Prs & Bnk Pn	
4E-05	1	4E-05	0.2727	4.54	7.71	10	Cp & Bp & Sh	
0.0006	4	0.0001						

Table3

Influence of factors on Wall Thickness @ C4.5								
						Columns (c)		
				Groups (g)		Shut Height		
						c1	c2	
						62.537	62.55	
		A1		Blank Position		0.92	0.91	
		Corner Pressure		# 1		0.91	0.91	
		304 kPa		B1		0.91	0.91	
				Blank Position		0.91	0.91	
				# 2		0.94	0.92	
				B2		0.94	0.91	
Rows (r)								
		A2		Blank Position		0.9	0.94	
		Corner Pressure		# 1		0.91	0.91	
		405 kPa		B1		0.91	0.94	
				Blank Position		0.92	0.92	
				# 2		0.91	0.91	
				B2		0.92	0.9	
c	n	r	g	N	T			
2	3	2	2	24	2950.1			
SS(c)	SS(r)	SS(g)	SS(cr)	SS(cg)	SS(rg)	SS(crg)	SS(total	SS(resd)
####	####	####	0.0005	####	####	####	0.0034	-0.002
				MSR min for significance				
SS	DF	MS	MSR	90%	95%	97.50%		
4E-06	1	4E-06	0.0101	4.54	7.71	10	Shut Height	
4E-06	1	4E-06	0.0101	4.54	7.71	10	Corner Pressures	
4E-05	1	4E-05	0.0909	4.54	7.71	10	Blank Position	
0.0005	1	0.0005	1.2218	4.54	7.71	10	Sht Ht & Cnr Prs	
0.0007	1	0.0007	1.7067	4.54	7.71	10	Sht Ht & Blnk Psn	
0.0003	1	0.0003	0.8194	4.54	7.71	10	Cnr Prs & Bnk Pn	
0.0001	1	0.0001	0.2521	4.54	7.71	10	Cp & Bp & Sh	
0.0017	4	0.0004						

Table4

Influence of factors on Wall Thickness @ E4.5								
						Columns (c)		
				Groups (g)		Shut Height		
						c1	c2	
						62.537	62.55	
		A1		Blank Position		0.92	0.9	
		Corner Pressure		# 1		0.92	0.91	
		304 kPa		B1		0.92	0.92	
				Blank Position		0.9	0.91	
				# 2		0.9	0.9	
				B2		0.9	0.92	
Rows (r)								
		A2		Blank Position		0.9	0.92	
		Corner Pressure		# 1		0.91	0.91	
		405 kPa		B1		0.9	0.9	
				Blank Position		0.92	0.9	
				# 2		0.9	0.9	
				B2		0.91	0.9	
c	n	r	g	N	T			
2	3	2	2	24	2950.1			
SS(c)	SS(r)	SS(g)	SS(cr)	SS(cg)	SS(rg)	SS(crg)	SS(total	SS(resd)
####	####	####	####	####	####	####	0.0018	-9E-04
				MSR min for significance				
SS	DF	MS	MSR	90%	95%	97.50%		
4E-06	1	4E-06	0.027	4.54	7.71	10	Shut Height	
0.0001	1	0.0001	0.6742	4.54	7.71	10	Corner Pressures	
0.0002	1	0.0002	1.3225	4.54	7.71	10	Blank Position	
4E-06	1	4E-06	0.027	4.54	7.71	10	Sht Ht & Cnr Prs	
4E-06	1	4E-06	0.027	4.54	7.71	10	Sht Ht & Blnk Psn	
0.0001	1	0.0001	0.6742	4.54	7.71	10	Cnr Prs & Bnk Pn	
0.0005	1	0.0005	3.2674	4.54	7.71	10	Cp & Bp & Sh	
0.0006	4	0.0002						

Table5

Influence of factors on Wall Thickness @ G4.5								
						Columns (c)		
				Groups (g)		Shut Height		
						c1	c2	
						62.537	62.55	
		A1		Blank Position		0.94	0.92	
		Corner Pressure		# 1		0.92	0.92	
		304 kPa		B1		0.92	0.92	
				Blank Position		0.92	0.92	
				# 2		0.94	0.91	
				B2		0.94	0.92	
Rows (r)								
		A2		Blank Position		0.92	0.92	
		Corner Pressure		# 1		0.92	0.92	
		405 kPa		B1		0.92	0.92	
				Blank Position		0.94	0.92	
				# 2		0.92	0.92	
				B2		0.92	0.92	
c	n	r	g	N	T			
2	3	2	2	24	2950.1			
SS(c)	SS(r)	SS(g)	SS(cr)	SS(cg)	SS(rg)	SS(crg)	SS(total	SS(resd)
####	####	####	####	####	####	####	0.0015	-6E-04
				MSR min for significance				
SS	DF	MS	MSR	90%	95%	97.50%		
0.0003	1	0.0003	6.2304	4.54	7.71	10	Shut Height	
4E-05	1	4E-05	0.6912	4.54	7.71	10	Corner Pressures	
4E-05	1	4E-05	0.6912	4.54	7.71	10	Blank Position	
0.0001	1	0.0001	1.9171	4.54	7.71	10	Sht Ht & Cnr Prs	
0.0001	1	0.0001	1.9171	4.54	7.71	10	Sht Ht & Blnk Psn	
4E-06	1	4E-06	0.0769	4.54	7.71	10	Cnr Prs & Bnk Pn	
4E-06	1	4E-06	0.0769	4.54	7.71	10	Cp & Bp & Sh	
0.0002	4	5E-05						

Table6

Influence of factors on Punch Tonnage								
						Columns (c)		
				Groups (g)		Shut Height		
						c1	c2	
						62.537	62.55	
		A1		Blank Position		612	616	
		Corner Pressure		# 1		620	619	
		304 kPa		B1		620	614	
				Blank Position		619	616	
				# 2		619	616	
				B2		623	618	
Rows (r)								
		A2		Blank Position		626	615	
		Corner Pressure		# 1		623	615	
		405 kPa		B1		619	619	
				Blank Position		625	615	
				# 2		623	615	
				B2		623	615	
c	n	r	g	N	T			
2	3	2	2	24	2950.1			
SS(c)	SS(r)	SS(g)	SS(cr)	SS(cg)	SS(rg)	SS(crg)	SS(total	SS(resd)
192.67	6	0	20.167	1.5	0.1667	2.6667	287.83	-223.2
				MSR min for significance				
SS	DF	MS	MSR	90%	95%	97.50%		
192.67	1	192.67	31.456	4.54	7.71	10	Shut Height	
6	1	6	0.9796	4.54	7.71	10	Corner Pressures	
0	1	0	0	4.54	7.71	10	Blank Position	
20.167	1	20.167	3.2925	4.54	7.71	10	Sht Ht & Cnr Prs	
1.5	1	1.5	0.2449	4.54	7.71	10	Sht Ht & Blnk Psn	
0.1667	1	0.1667	0.0272	4.54	7.71	10	Cnr Prs & Bnk Pn	
2.6667	1	2.6667	0.4354	4.54	7.71	10	Cp & Bp & Sh	
24.5	4	6.125						

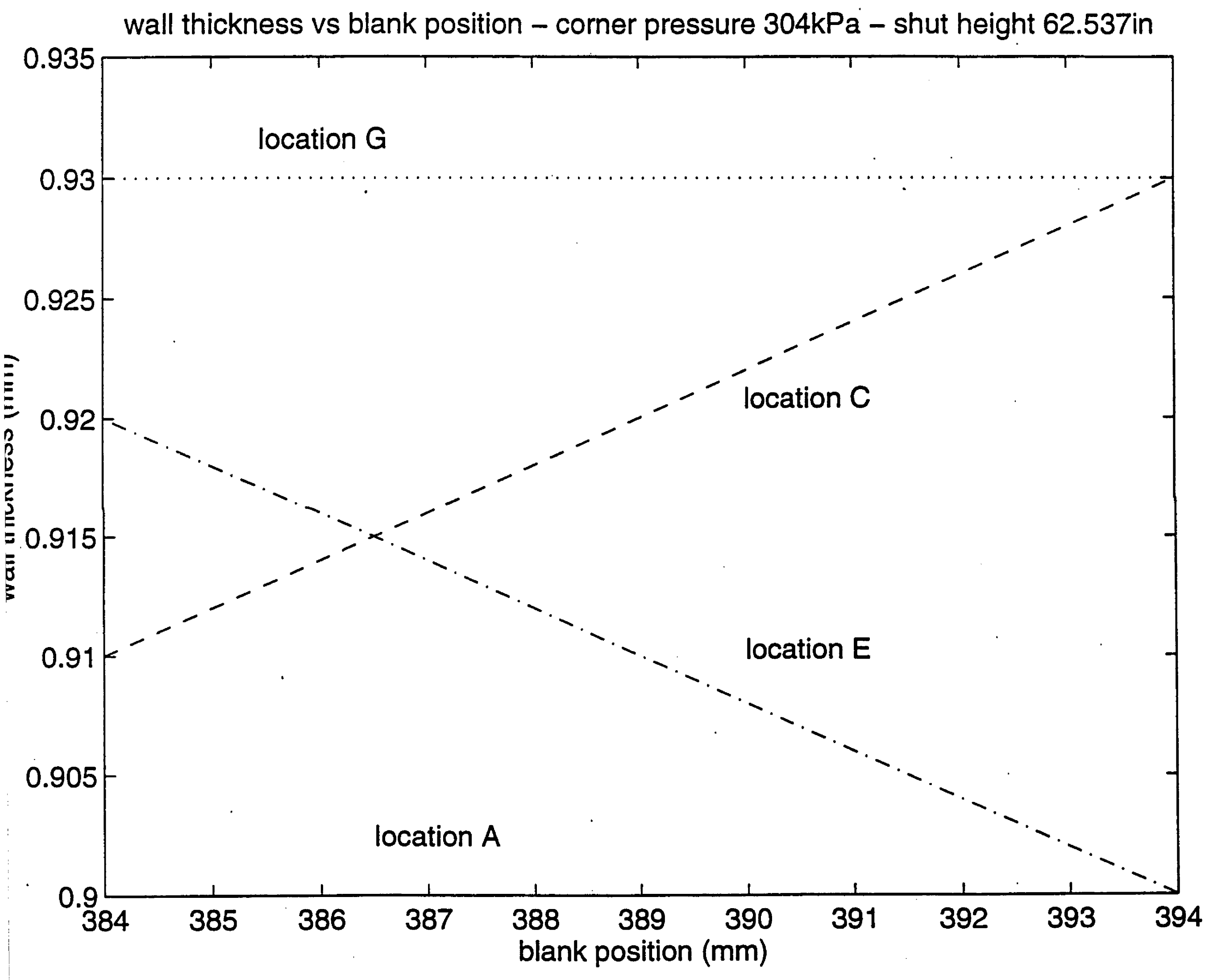
Table7

Influence of factors on Blankholder Tonnage								
						Columns (c)		
				Groups (g)		Shut Height		
						c1	c2	
						62.537	62.55	
		A1		Blank Position		195	128	
		Corner Pressure		# 1		197	129.5	
		304 kPa		B1		196	131	
				Blank Position		191	152	
				# 2		191	154	
				B2		195	154	
Rows (r)								
		A2		Blank Position		200	161	
		Corner Pressure		# 1		200	159	
		405 kPa		B1		204	162	
				Blank Position		198	161	
				# 2		199	160	
				B2		199	159	
c	n	r	g	N	T			
2	3	2	2	24	2950.1			
SS(c)	SS(r)	SS(g)	SS(cr)	SS(cg)	SS(rg)	SS(crg)	SS(total	SS(resd)
12811	918.84	106.26	256.76	326.34	207.09	243.84	14908	-14870
				MSR min for significance				
SS	DF	MS	MSR	90%	95%	97.50%		
12811	1	12811	49.558	4.54	7.71	10	Shut Height	
918.84	1	918.84	3.5544	4.54	7.71	10	Corner Pressures	
106.26	1	106.26	0.411	4.54	7.71	10	Blank Position	
256.76	1	256.76	0.9932	4.54	7.71	10	Sht Ht & Cnr Prs	
326.34	1	326.34	1.2624	4.54	7.71	10	Sht Ht & Blnk Psn	
207.09	1	207.09	0.8011	4.54	7.71	10	Cnr Prs & Bnk Pn	
243.84	1	243.84	0.9433	4.54	7.71	10	Cp & Bp & Sh	
1034	4	258.51						

Table8

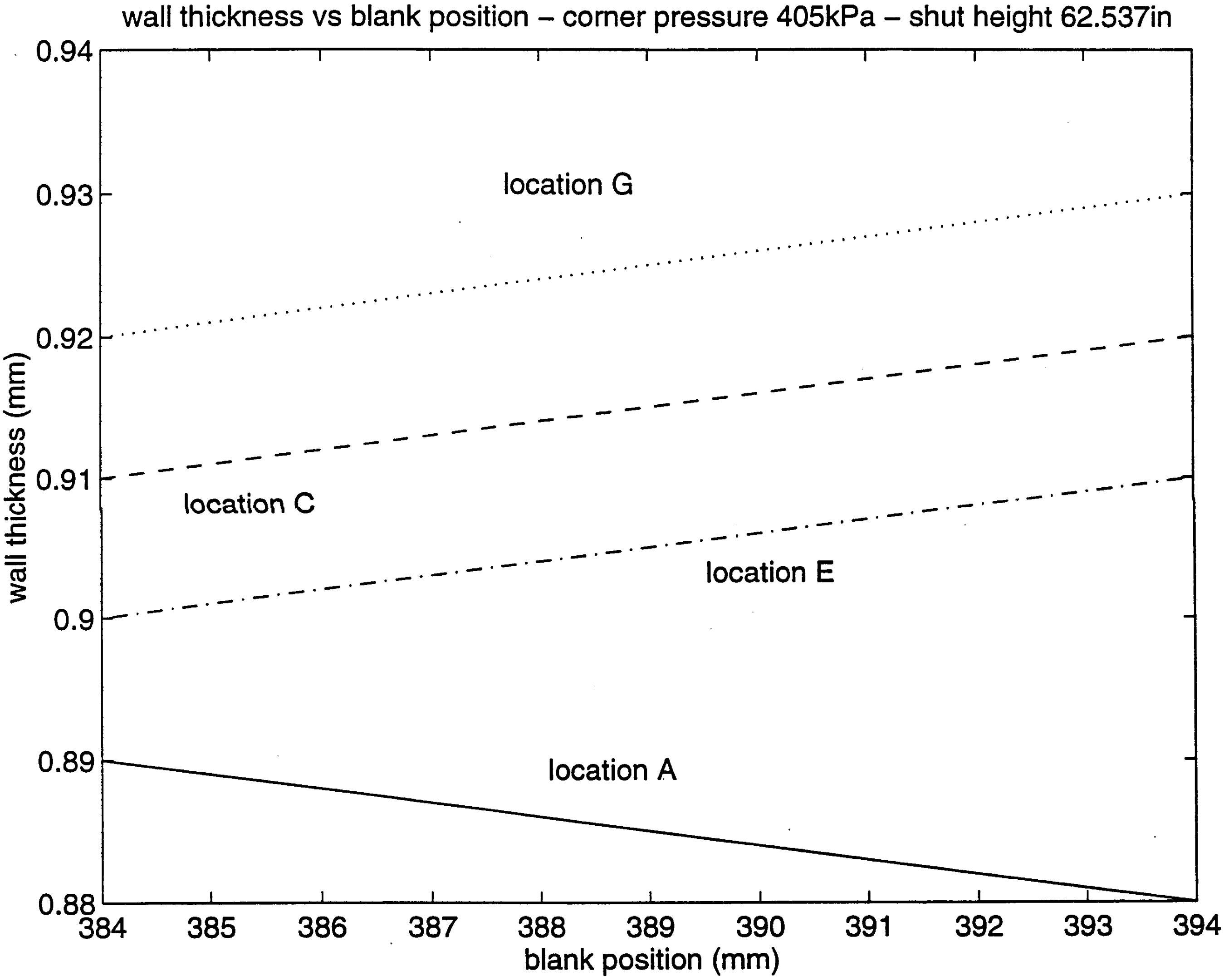
APPENDIX3

Graph No.1



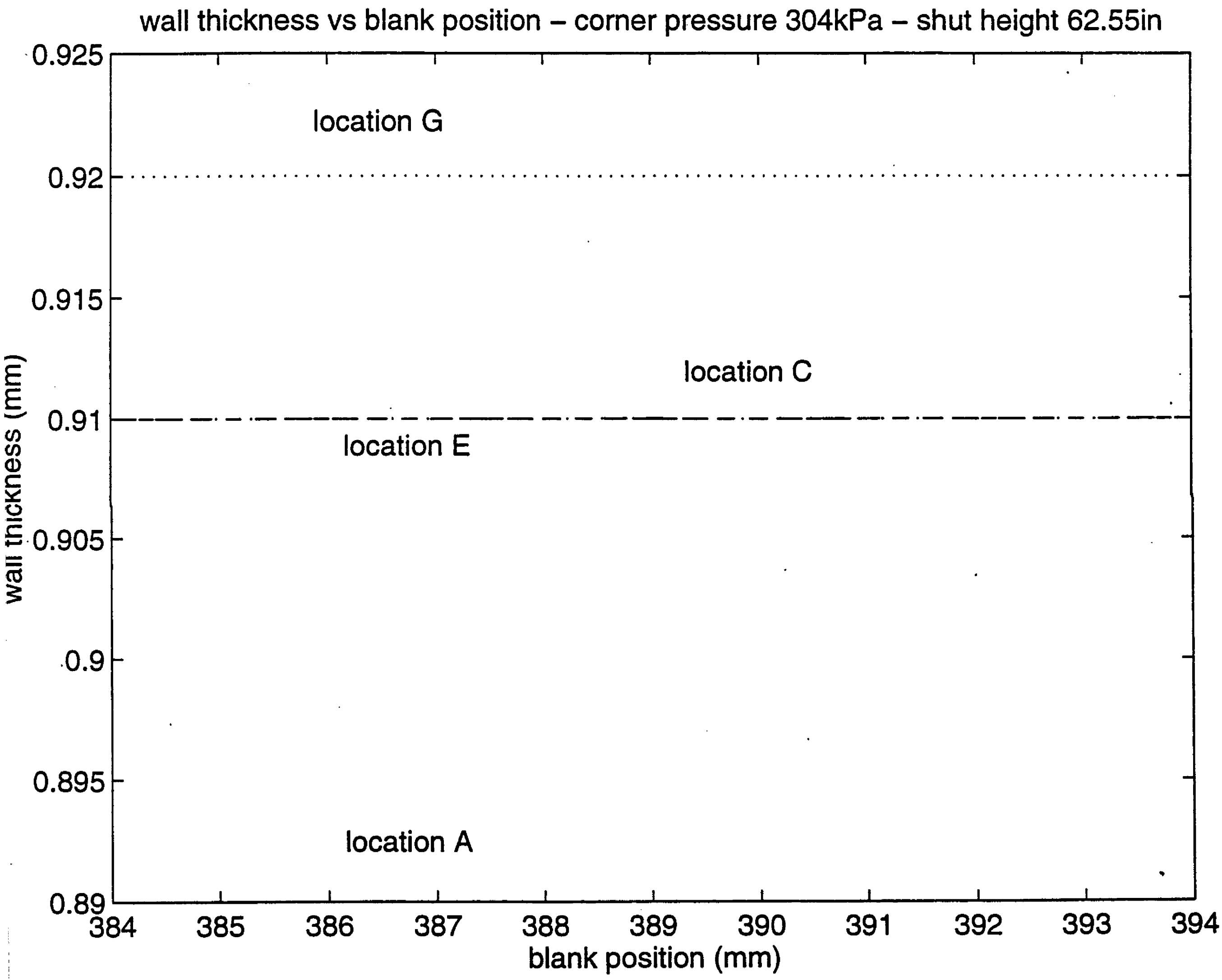
wall thickness vs blank position – corner pressure 304kPa – shut height 62.537in
location G
location C
location E
location A
0.935
0.93
0.925
0.92
0.915
0.91
0.905
0.9
384
385
386
387
388
389
390
391
392
393
394
blank position (mm)

Graph No.2



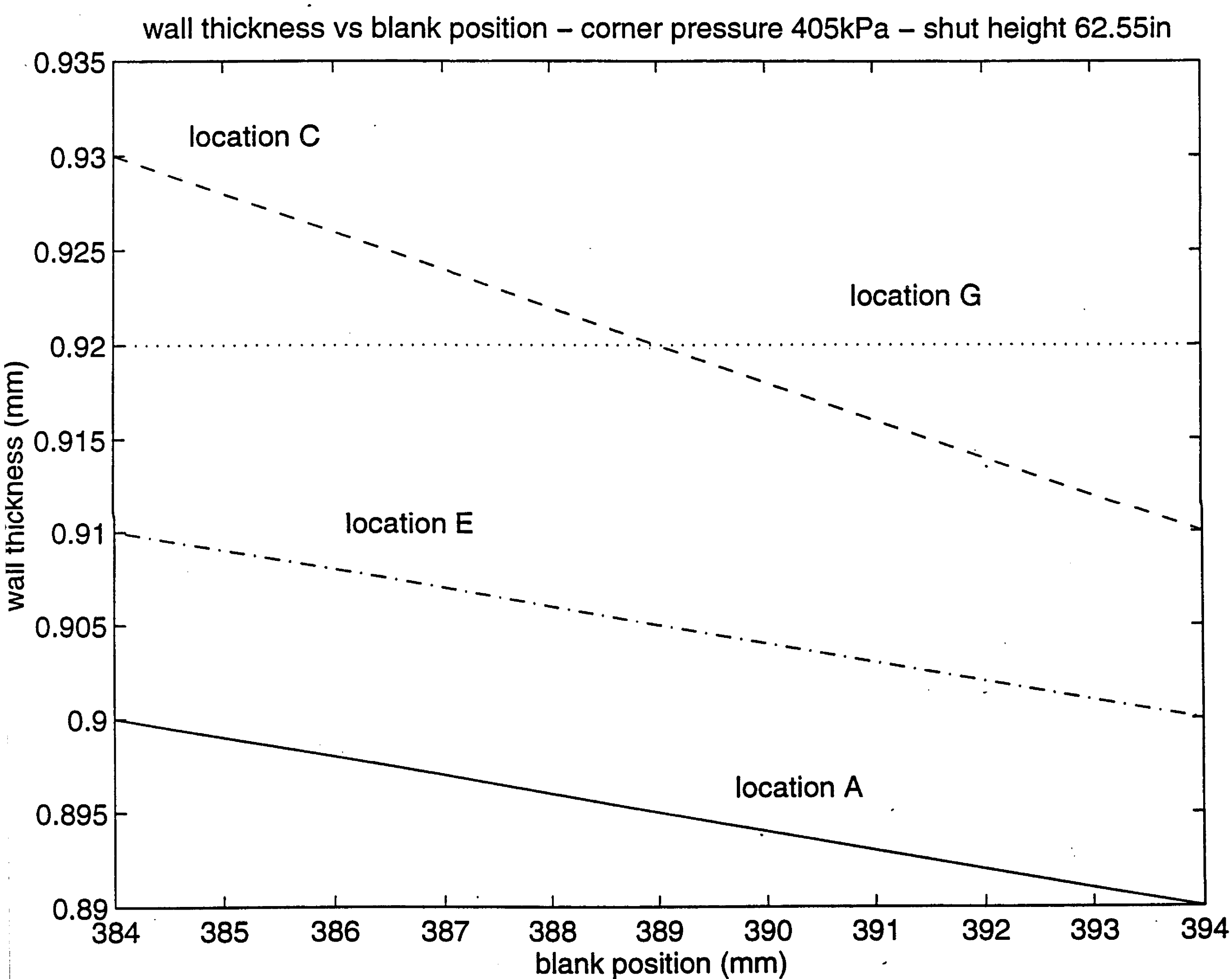
wall thickness vs blank position – corner pressure 405kPa – shut height 62.537in
wall thickness (mm)
0.94
0.93
0.92
0.91
0.9
0.89
0.88
location G
location C
location E
location A
384
385
386
387
388
389
390
391
392
393
394
blank position (mm)

Graph No.3

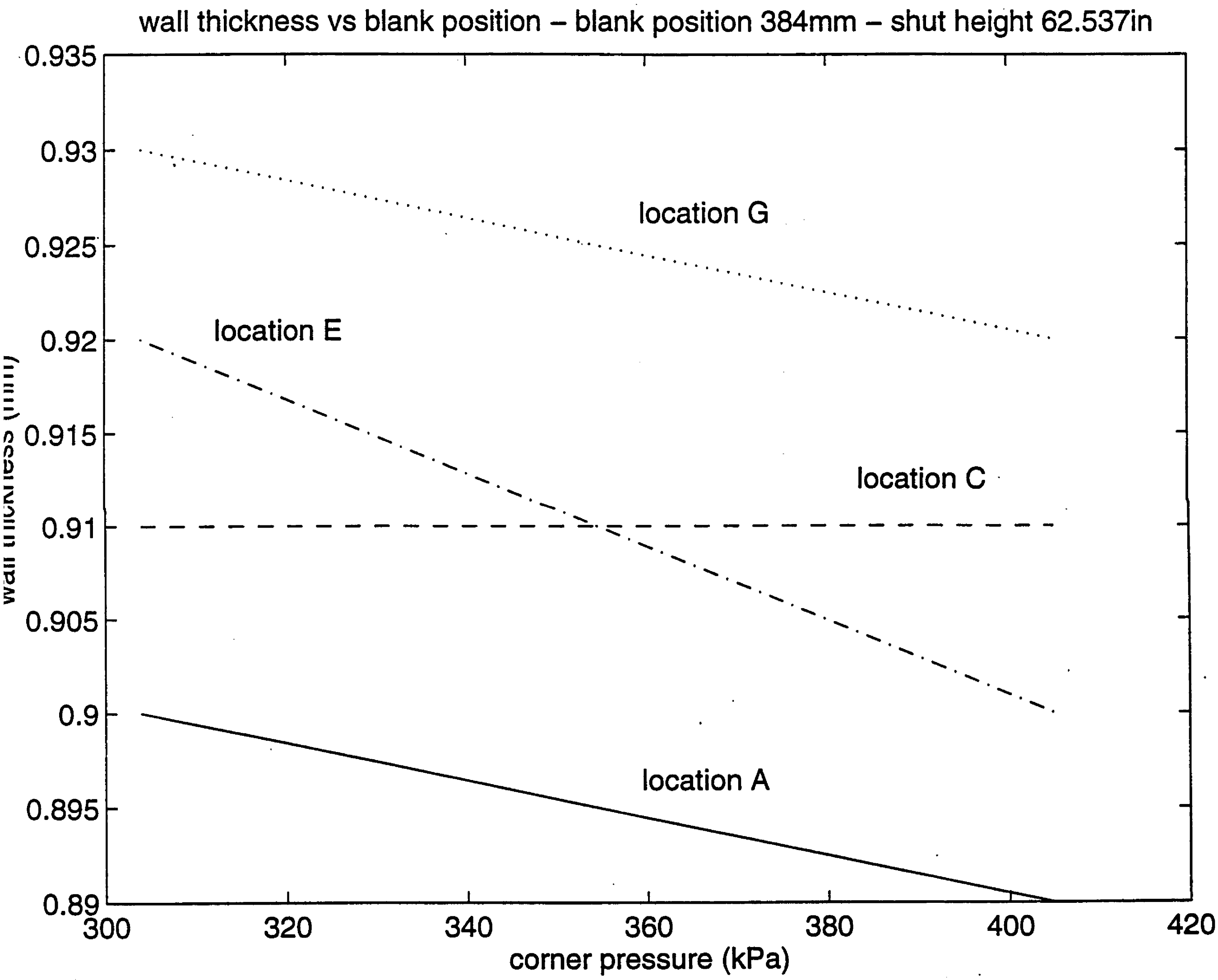


wall thickness vs blank position – corner pressure 304kPa – shut height 62.55in
0.925
0.92
0.915
0.91
0.905
0.9
0.895
0.89
wall thickness (mm)
384
385
386
387
388
389
390
391
392
393
394
blank position (mm)
location G
location C
location E
location A

Graph No.4

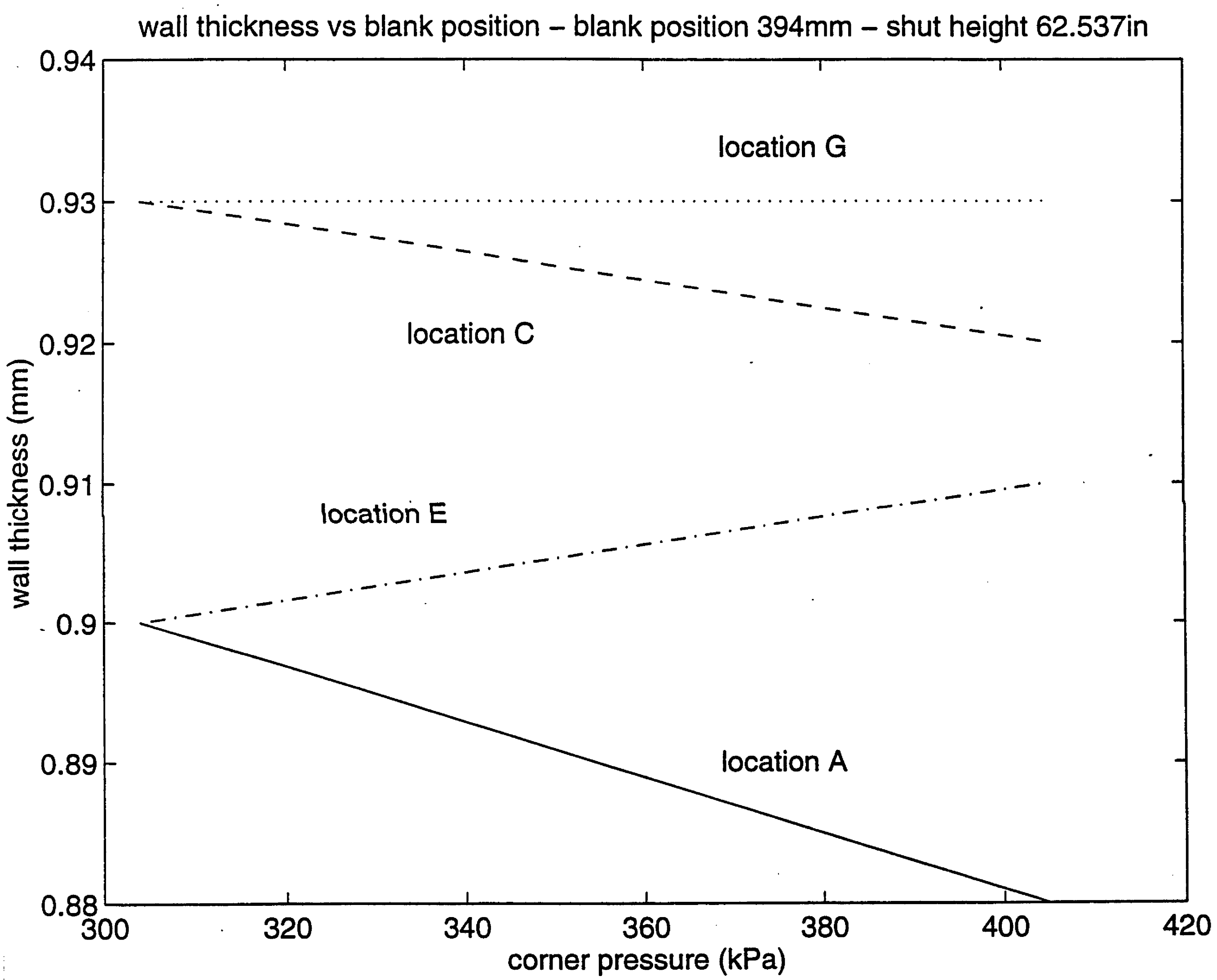

wall thickness vs blank position – corner pressure 405kPa – shut height 62.55in
location C
location G
location E
location A
wall thickness (mm)
blank position (mm)
0.935
0.93
0.925
0.92
0.915
0.91
0.905
0.9
0.895
0.89
384
385
386
387
388
389
390
391
392
393
394

Graph No.5



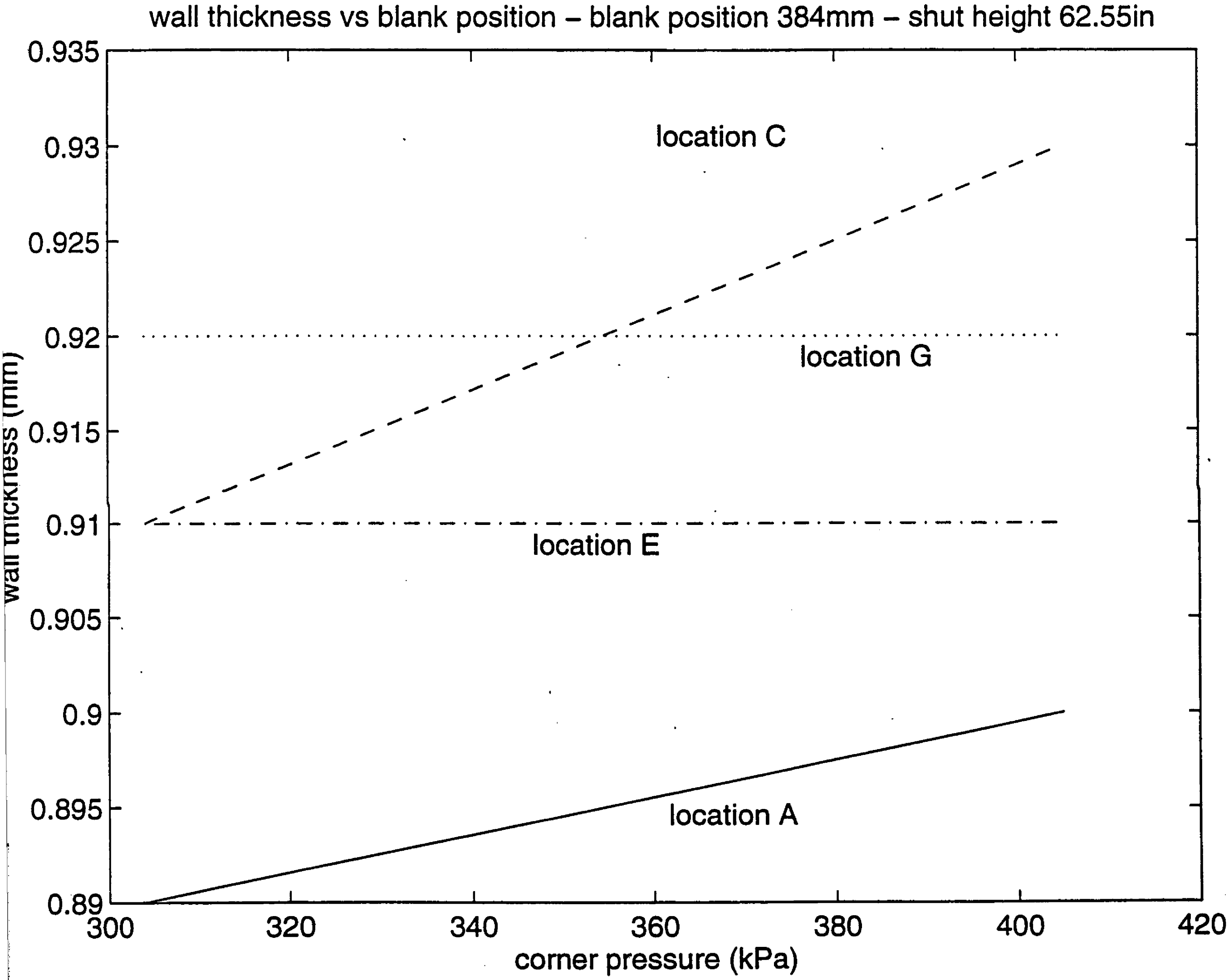
wall thickness vs blank position – blank position 384mm – shut height 62.537in
wall thickness (mm)
0.935
0.93
0.925
0.92
0.915
0.91
0.905
0.9
0.895
0.89
300
320
340
360
380
400
420
corner pressure (kPa)
location G
location E
location C
location A

Graph No.6



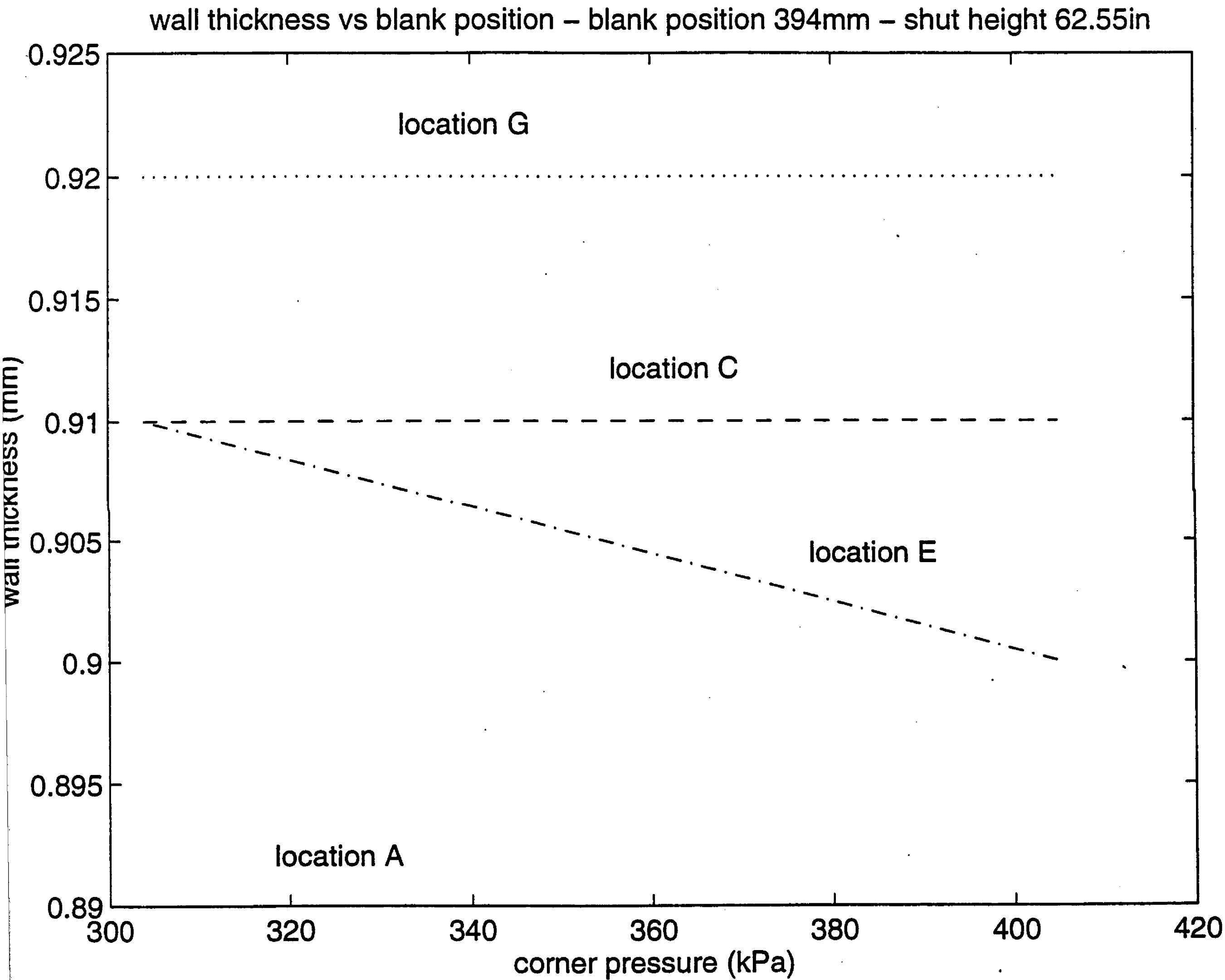
wall thickness vs blank position – blank position 394mm – shut height 62.537in
0.94
0.93
0.92
0.91
0.9
0.89
0.88
300
320
340
360
380
400
420
wall thickness (mm)
corner pressure (kPa)
location G
location C
location E
location A

Graph No.7

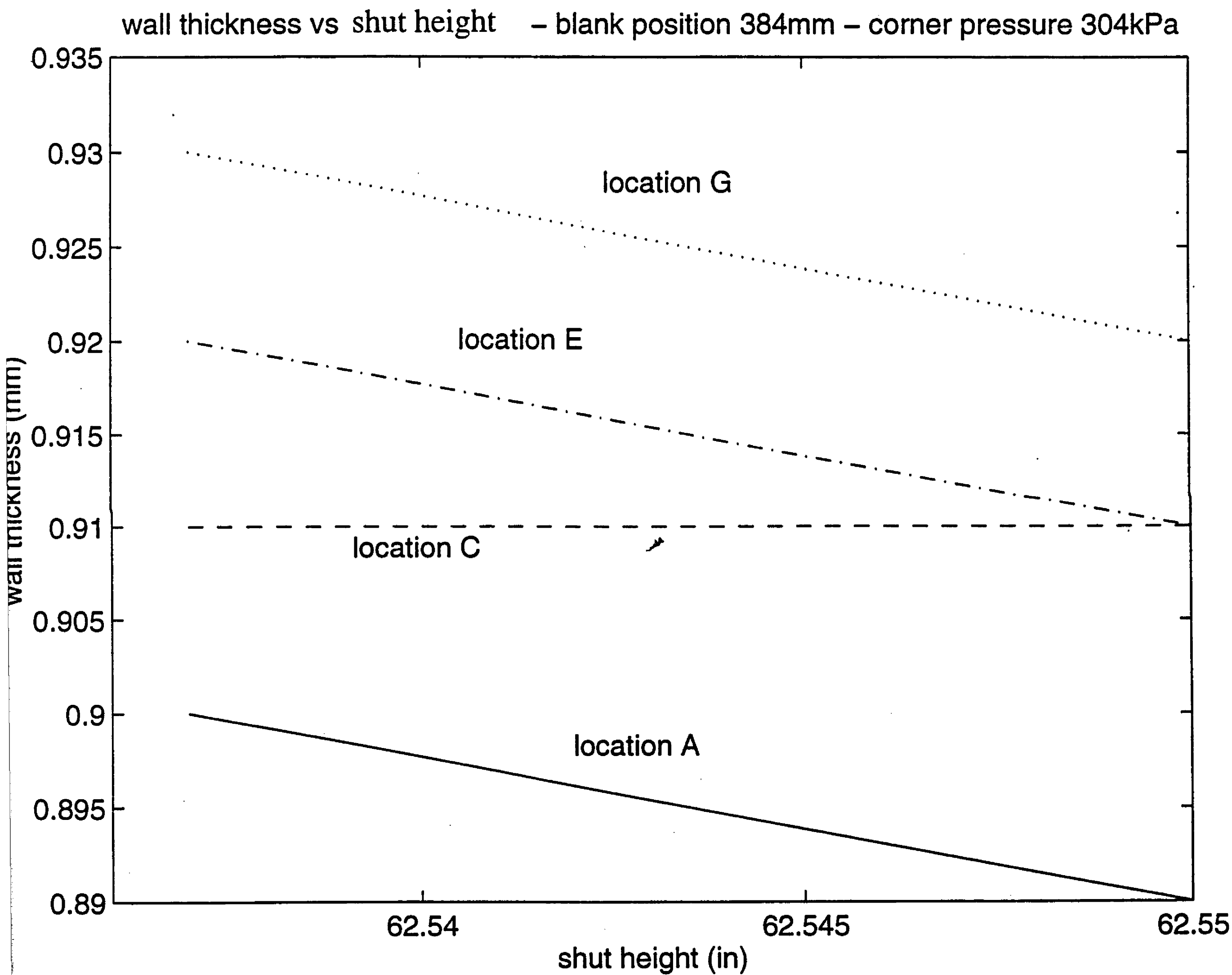


wall thickness vs blank position – blank position 384mm – shut height 62.55in
wall thickness (mm)
corner pressure (kPa)
0.935
0.93
0.925
0.92
0.915
0.91
0.905
0.9
0.895
0.89
300
320
340
360
380
400
420
location C
location G
location E
location A

Graph No.8

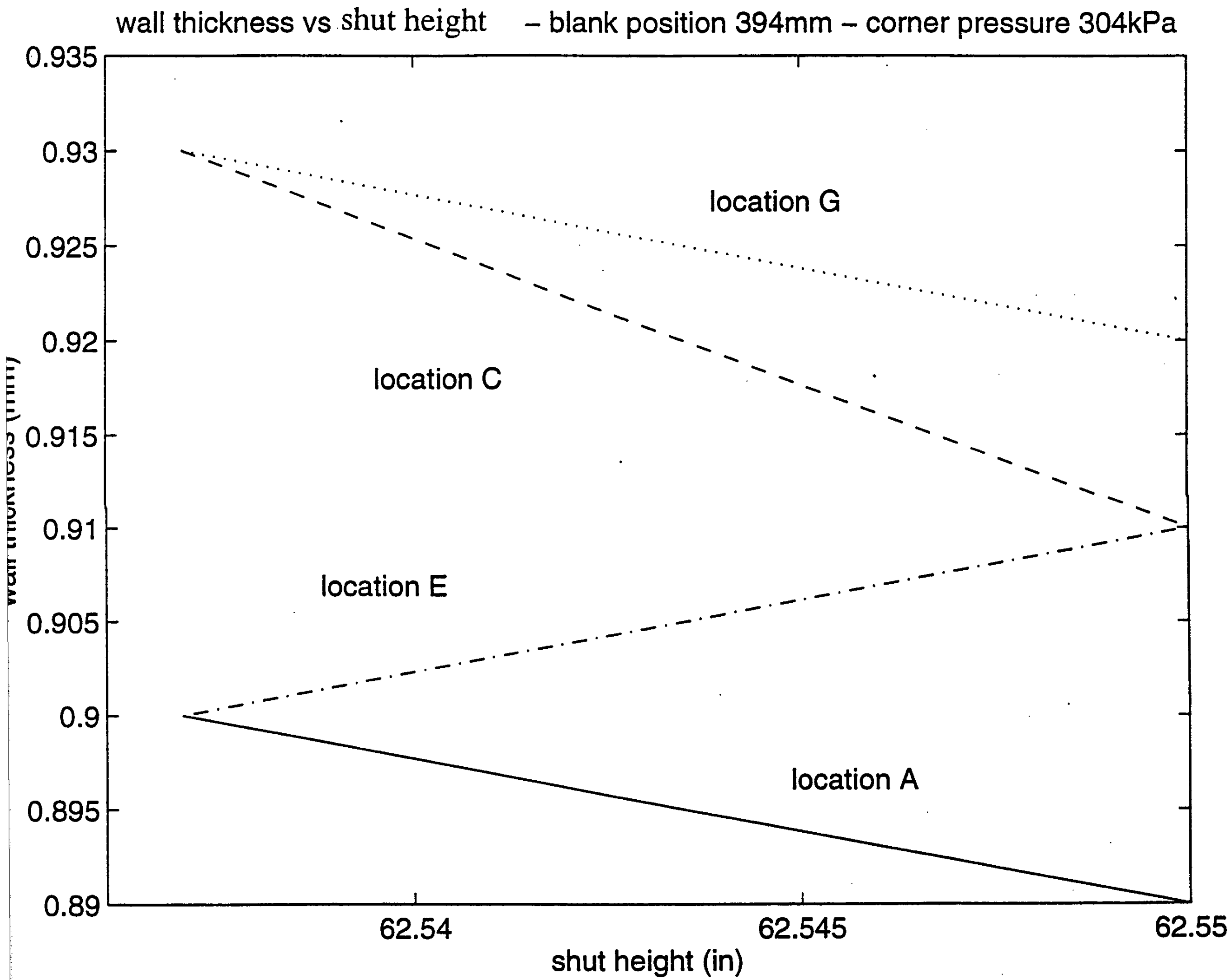

wall thickness vs blank position – blank position 394mm – shut height 62.55in
wall thickness (mm)
corner pressure (kPa)
location G
location C
location E
location A
0.925
0.92
0.915
0.91
0.905
0.9
0.895
0.89
300
320
340
360
380
400
420

Graph No.9

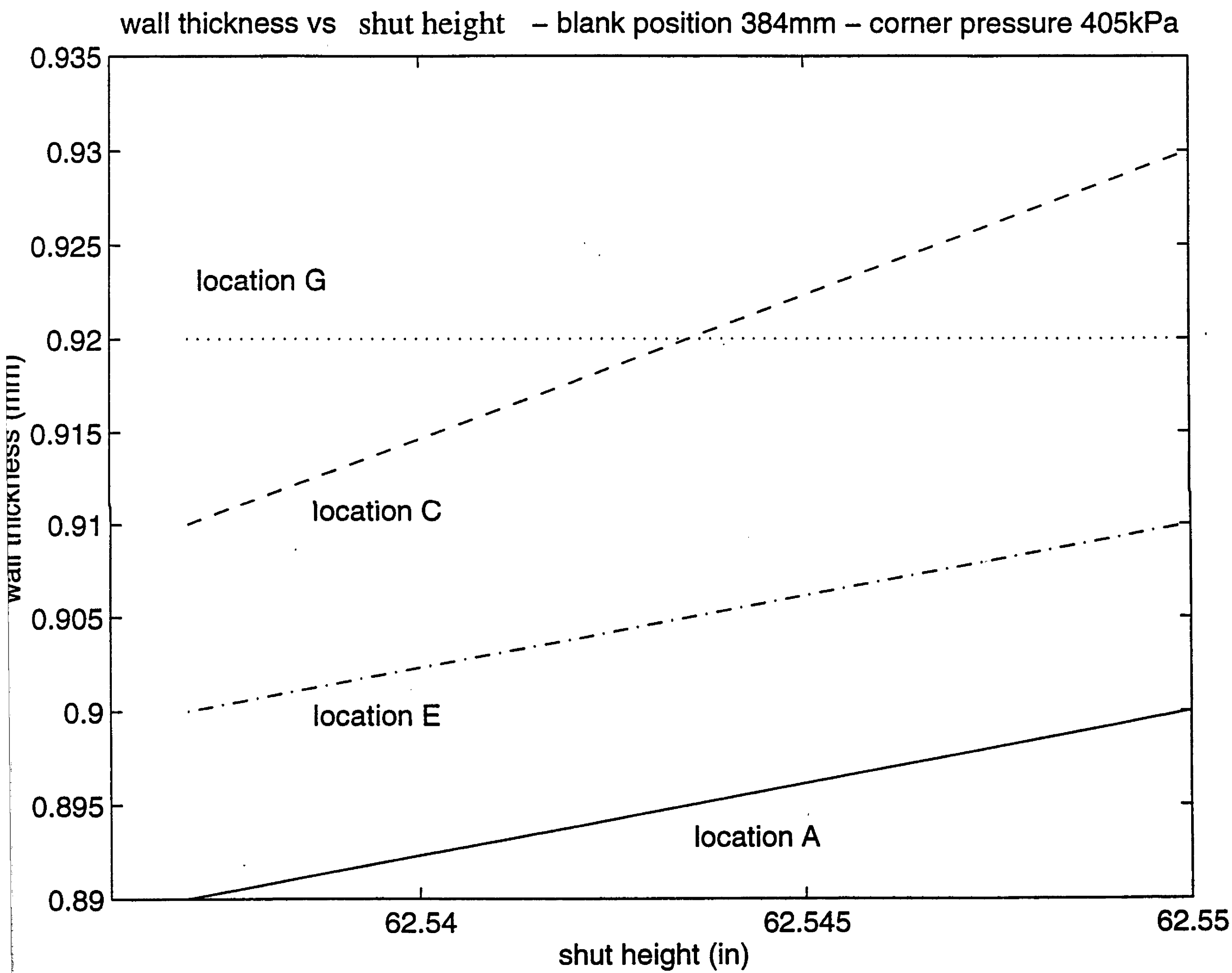


wall thickness vs shut height – blank position 384mm – corner pressure 304kPa
0.935
0.93
0.925
0.92
0.915
0.91
0.905
0.9
0.895
0.89
wall thickness (mm)
location G
location E
location C
location A
62.54
62.545
62.55
shut height (in)

Graph No.10

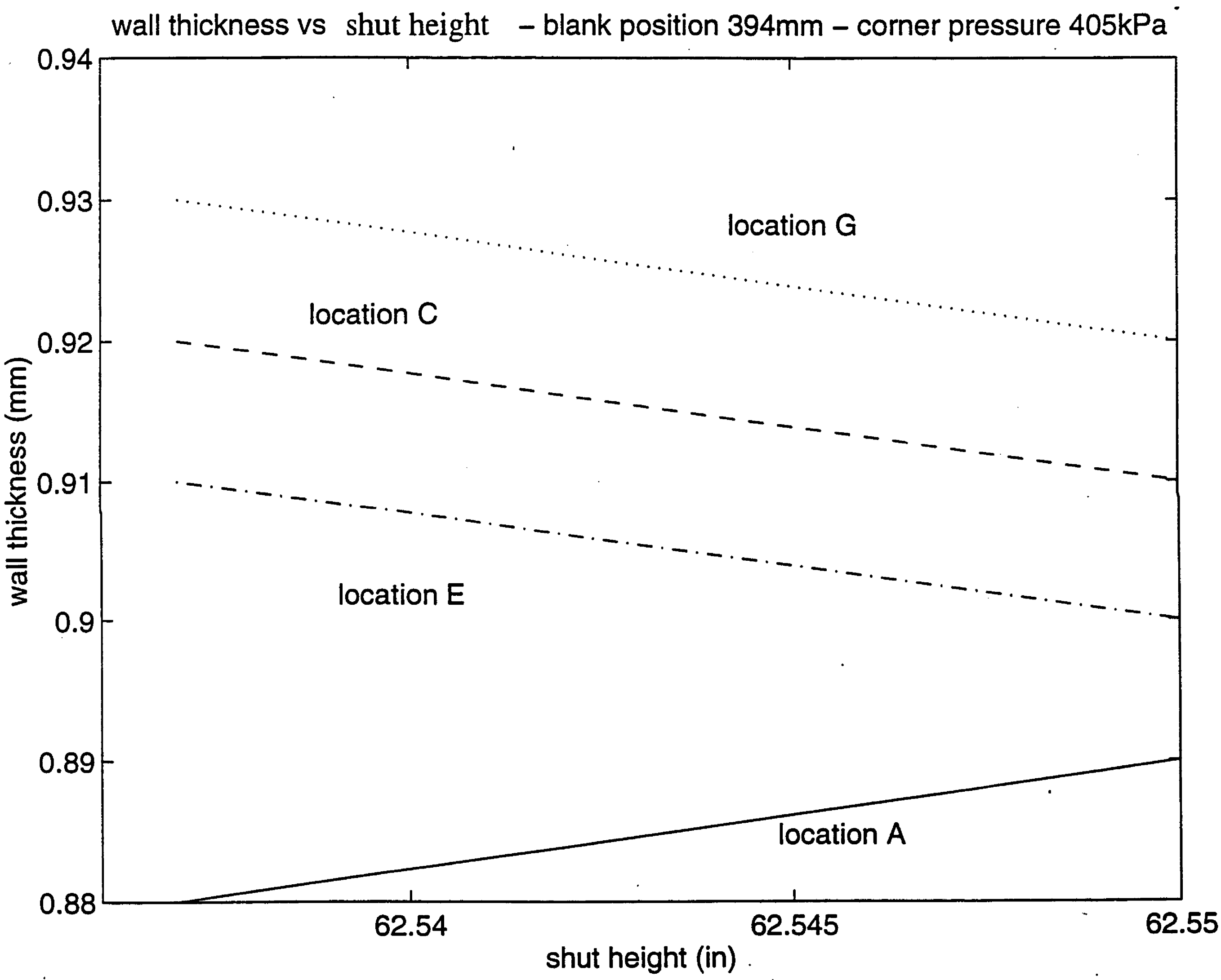

wall thickness vs shut height – blank position 394mm – corner pressure 304kPa
0.935
0.93
0.925
0.92
0.915
0.91
0.905
0.9
0.895
0.89
location G
location C
location E
location A
62.54
62.545
62.55
shut height (in)

Graph No.11



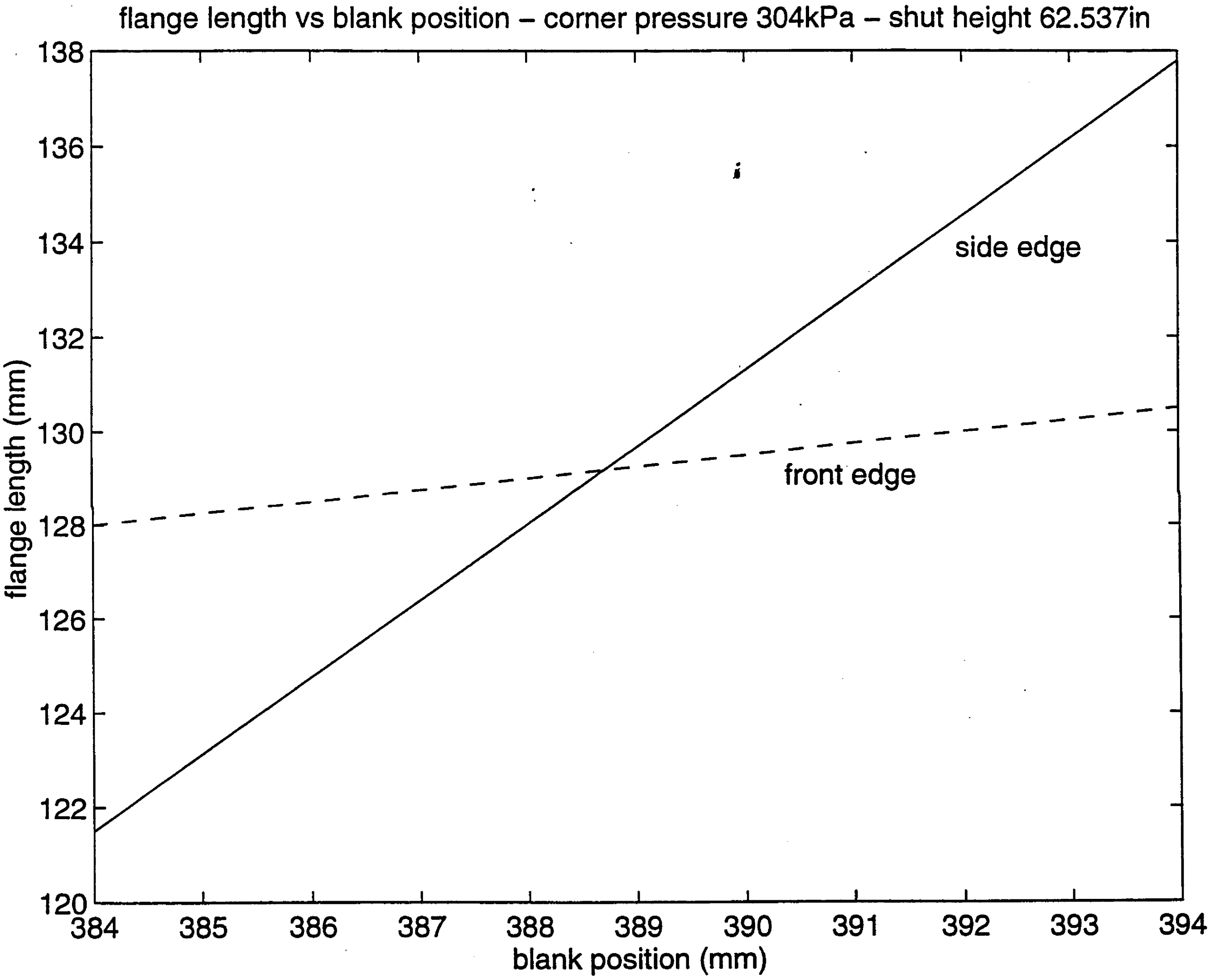
wall thickness vs shut height - blank position 384mm - corner pressure 405kPa
0.935
0.93
0.925
0.92
0.915
0.91
0.905
0.9
0.895
0.89
wall thickness (mm)
location G
location C
location E
location A
62.54
62.545
62.55
shut height (in)

Graph No.12



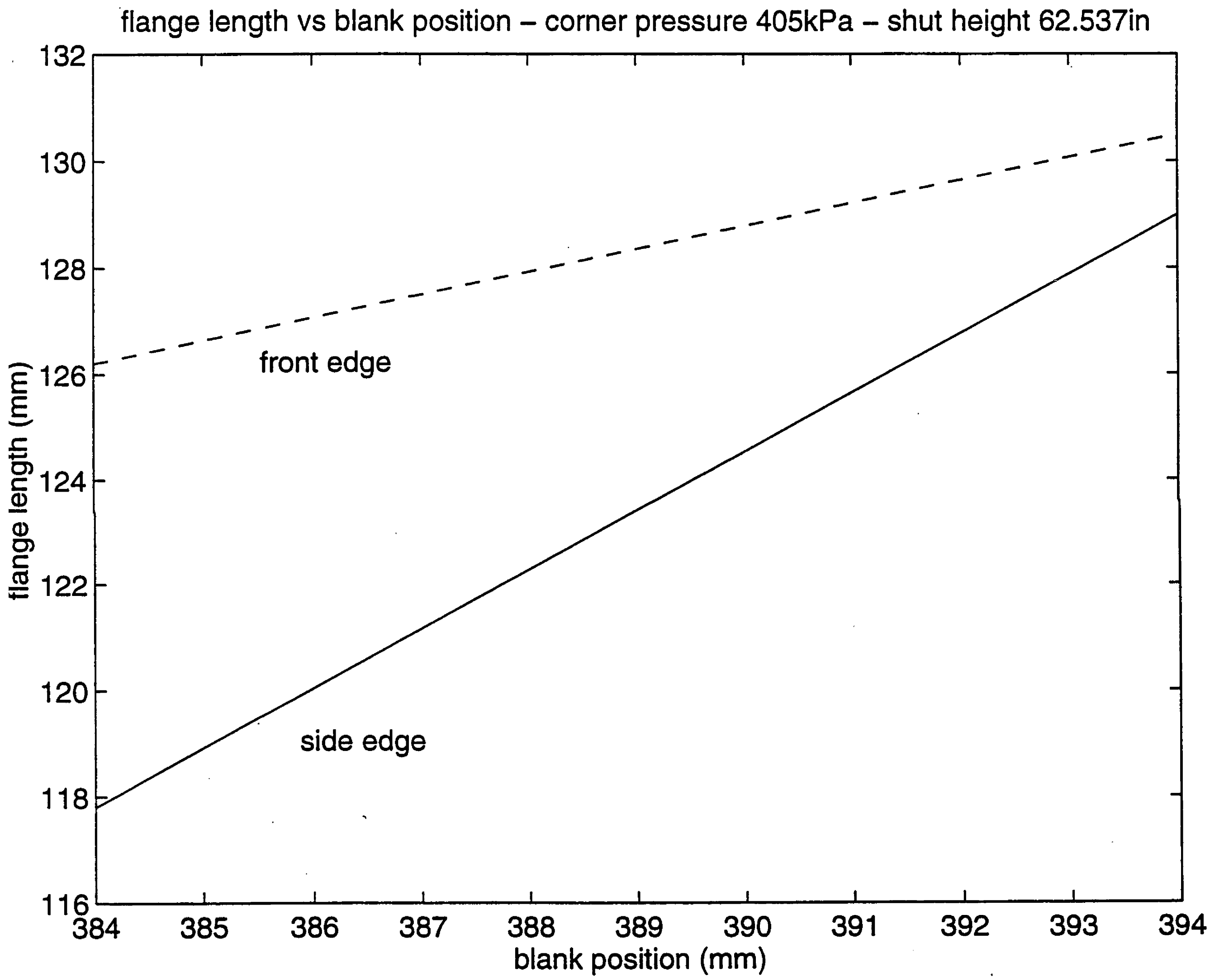
wall thickness vs shut height – blank position 394mm – corner pressure 405kPa
wall thickness (mm)
0.94
0.93
0.92
0.91
0.9
0.89
0.88
location G
location C
location E
location A
62.54
62.545
62.55
shut height (in)

Graph No.13



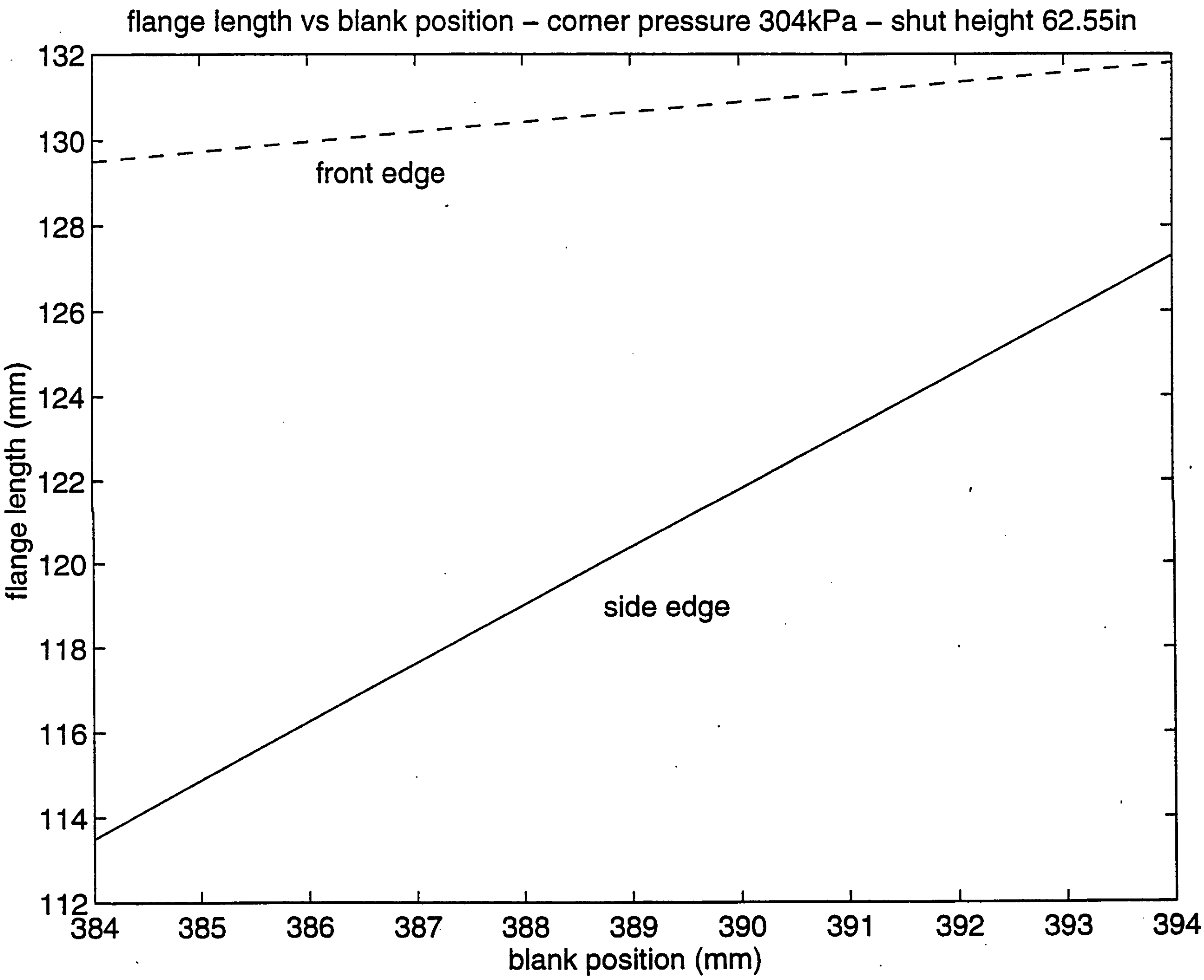
flange length vs blank position – corner pressure 304kPa – shut height 62.537in
flange length (mm)
blank position (mm)
side edge
front edge
138
136
134
132
130
128
126
124
122
120
384
385
386
387
388
389
390
391
392
393
394

Graph No.14



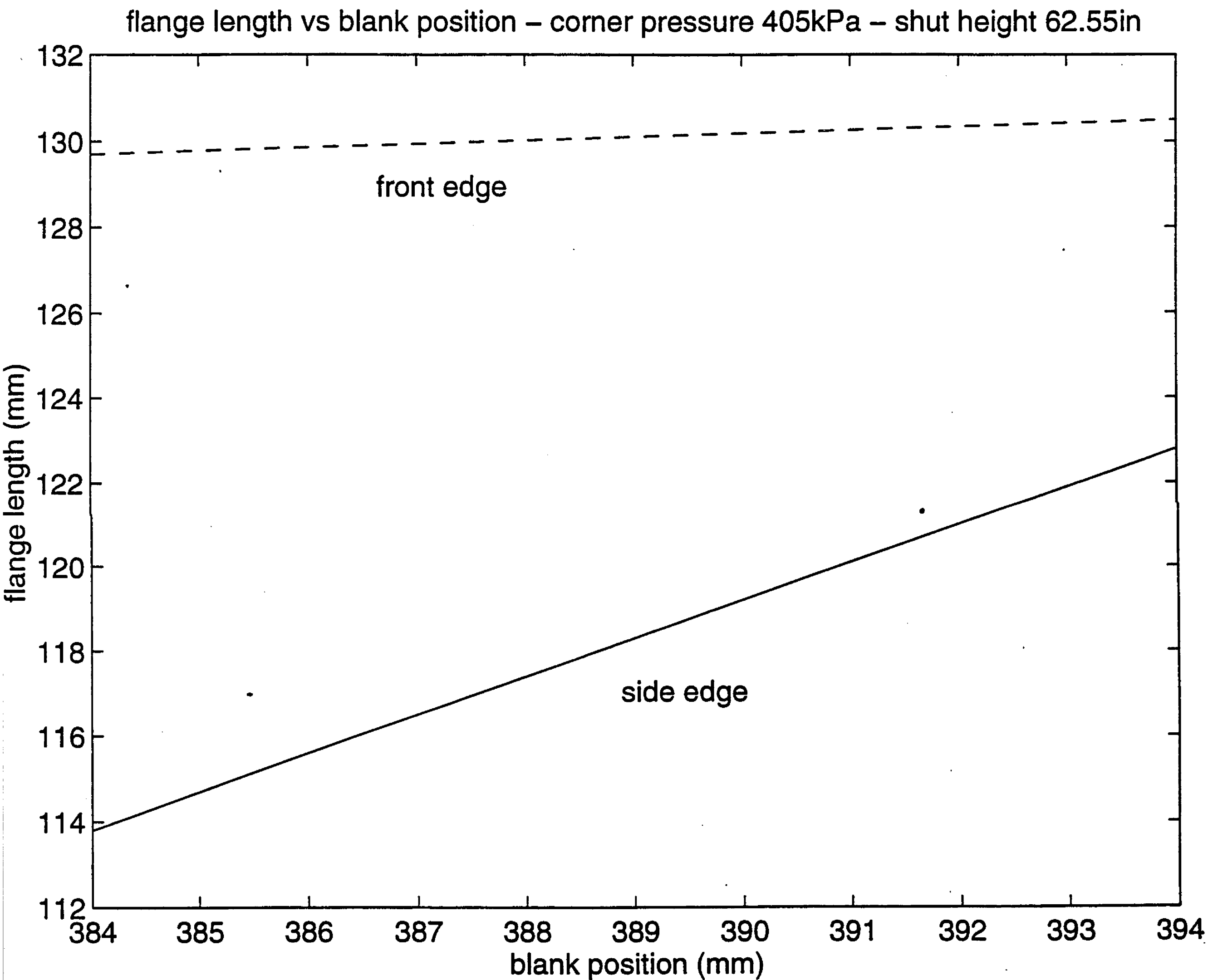
flange length vs blank position – corner pressure 405kPa – shut height 62.537in
flange length (mm)
132
130
128
126
124
122
120
118
116
front edge
side edge
384
385
386
387
388
389
390
391
392
393
394
blank position (mm)

Graph No.15



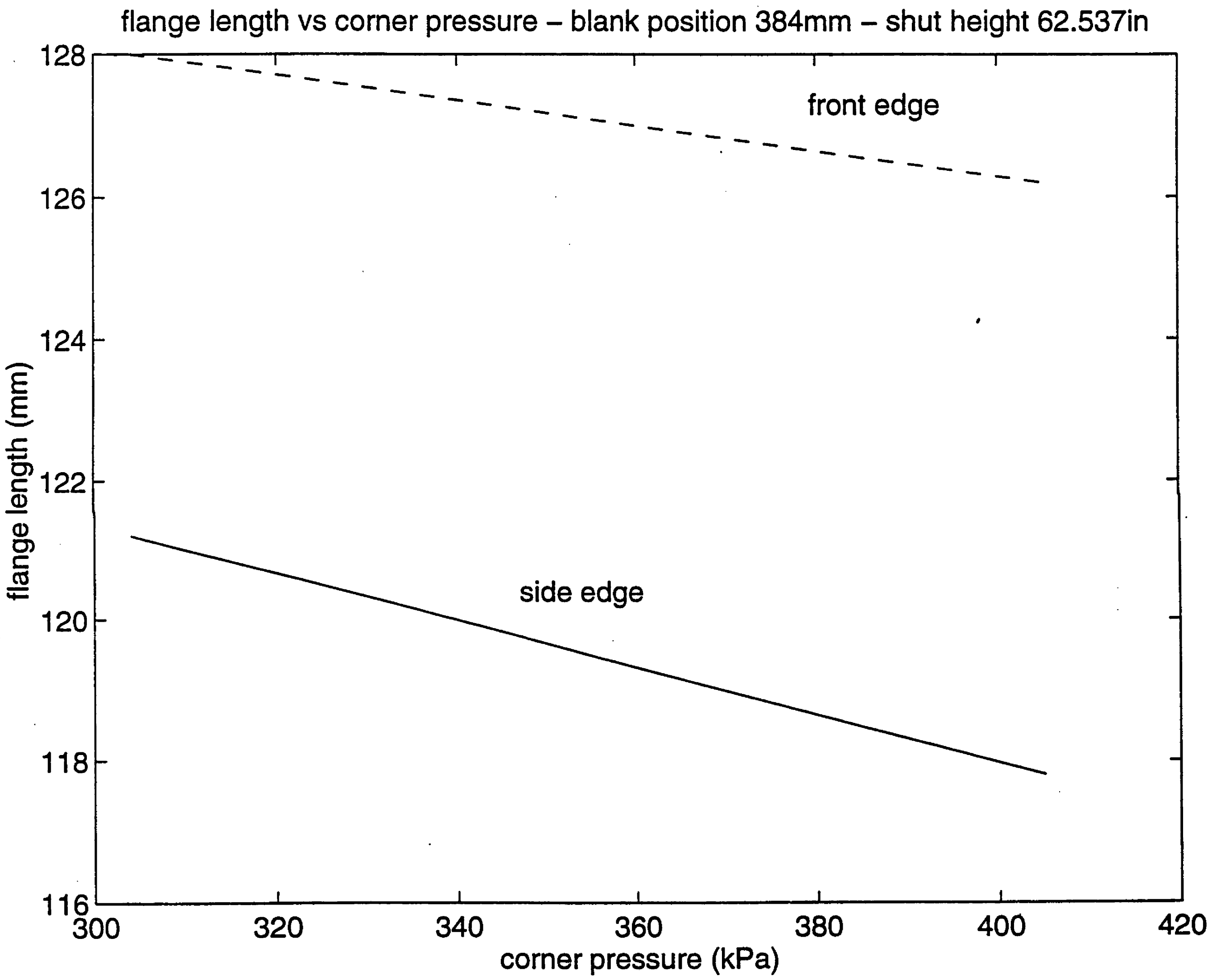
flange length vs blank position – corner pressure 304kPa – shut height 62.55in
132
130
128
126
124
122
120
118
116
114
112
flange length (mm)
front edge
side edge
384
385
386
387
388
389
390
391
392
393
394
blank position (mm)

Graph No.16

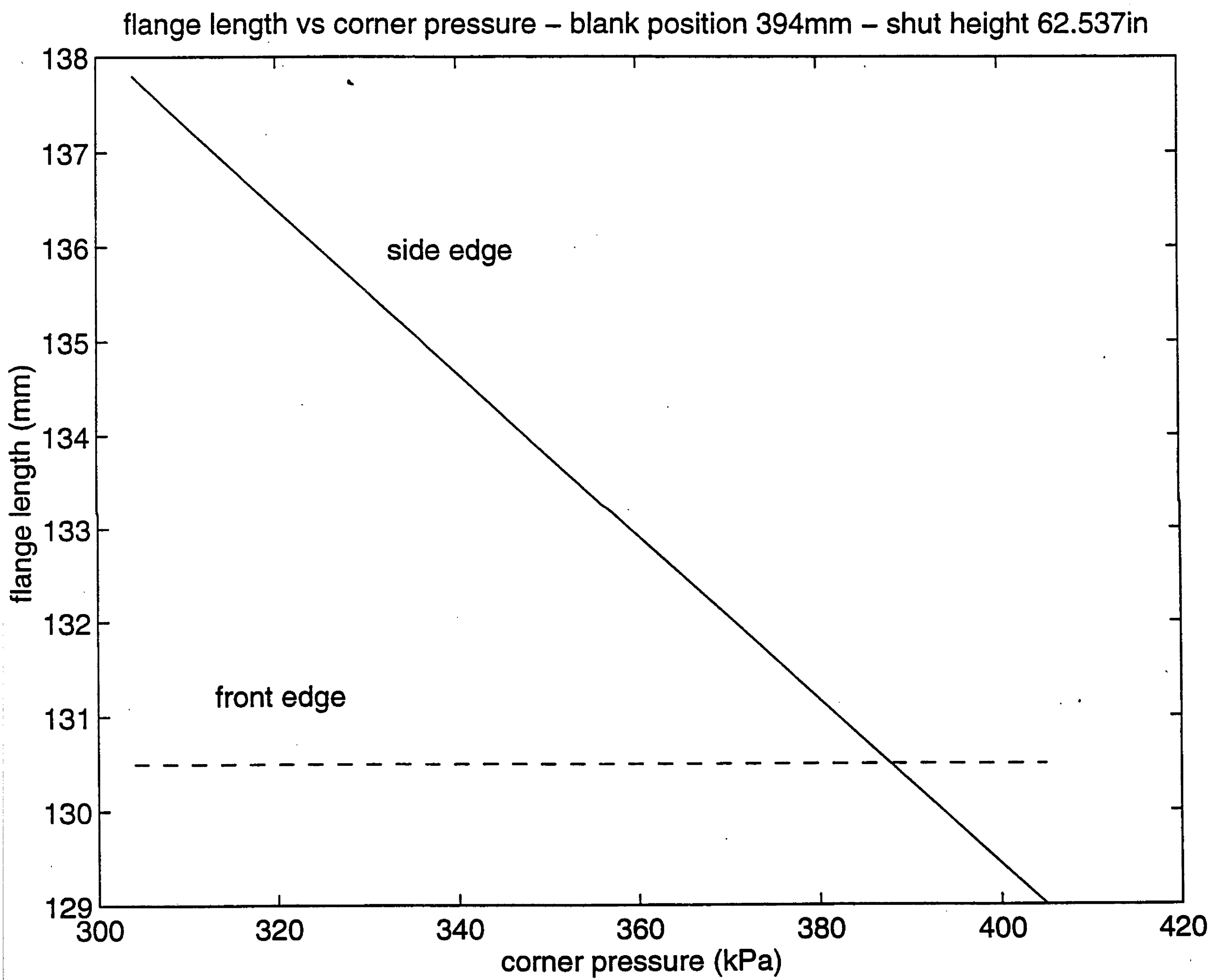


flange length vs blank position – corner pressure 405kPa – shut height 62.55in
132
130
128
126
124
122
120
118
116
114
112
flange length (mm)
front edge
side edge
384
385
386
387
388
389
390
391
392
393
394
blank position (mm)

Graph No.17

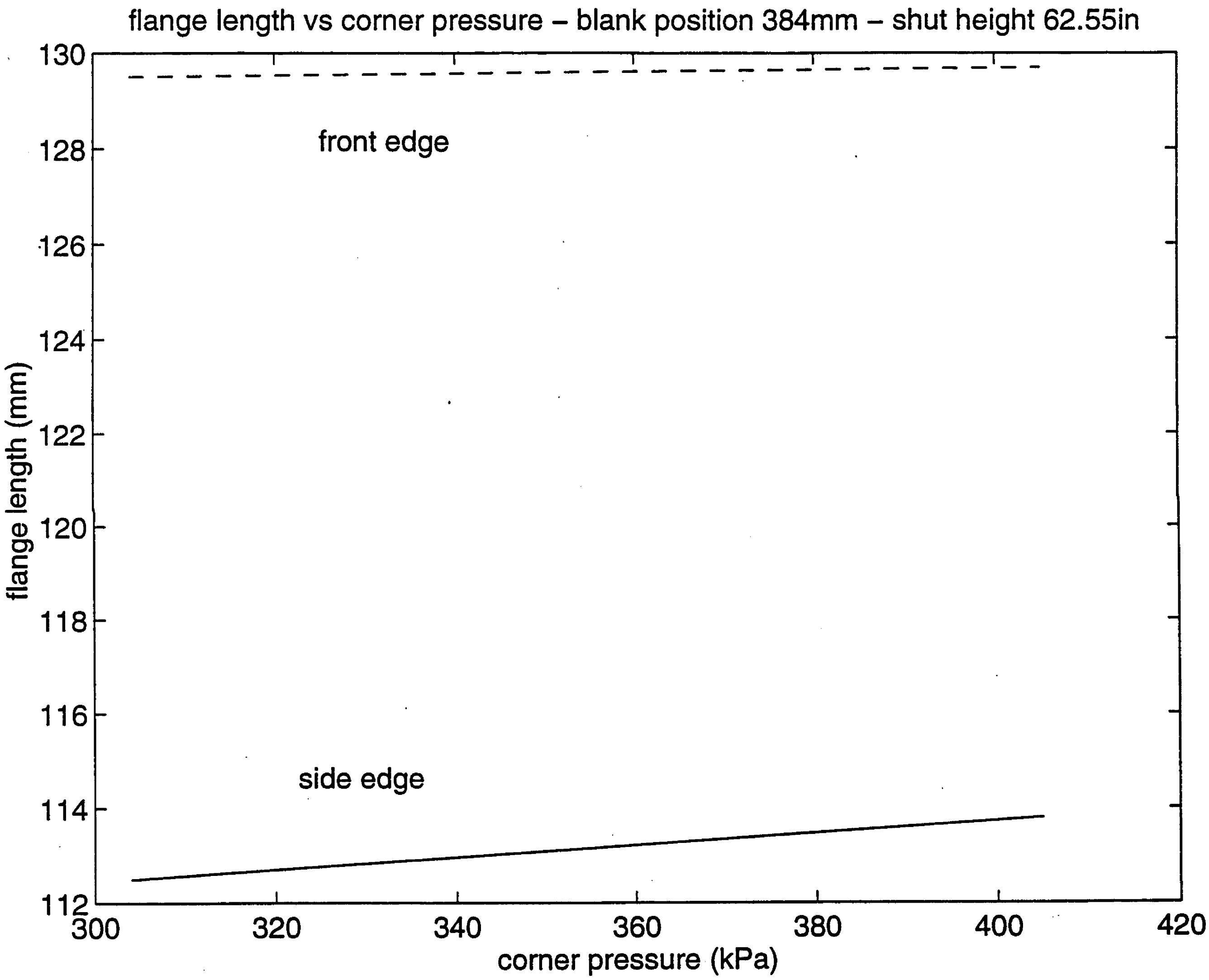

flange length vs corner pressure – blank position 384mm – shut height 62.537in
front edge
side edge
flange length (mm)
corner pressure (kPa)
128
126
124
122
120
118
116
300
320
340
360
380
400
420

Graph No.18

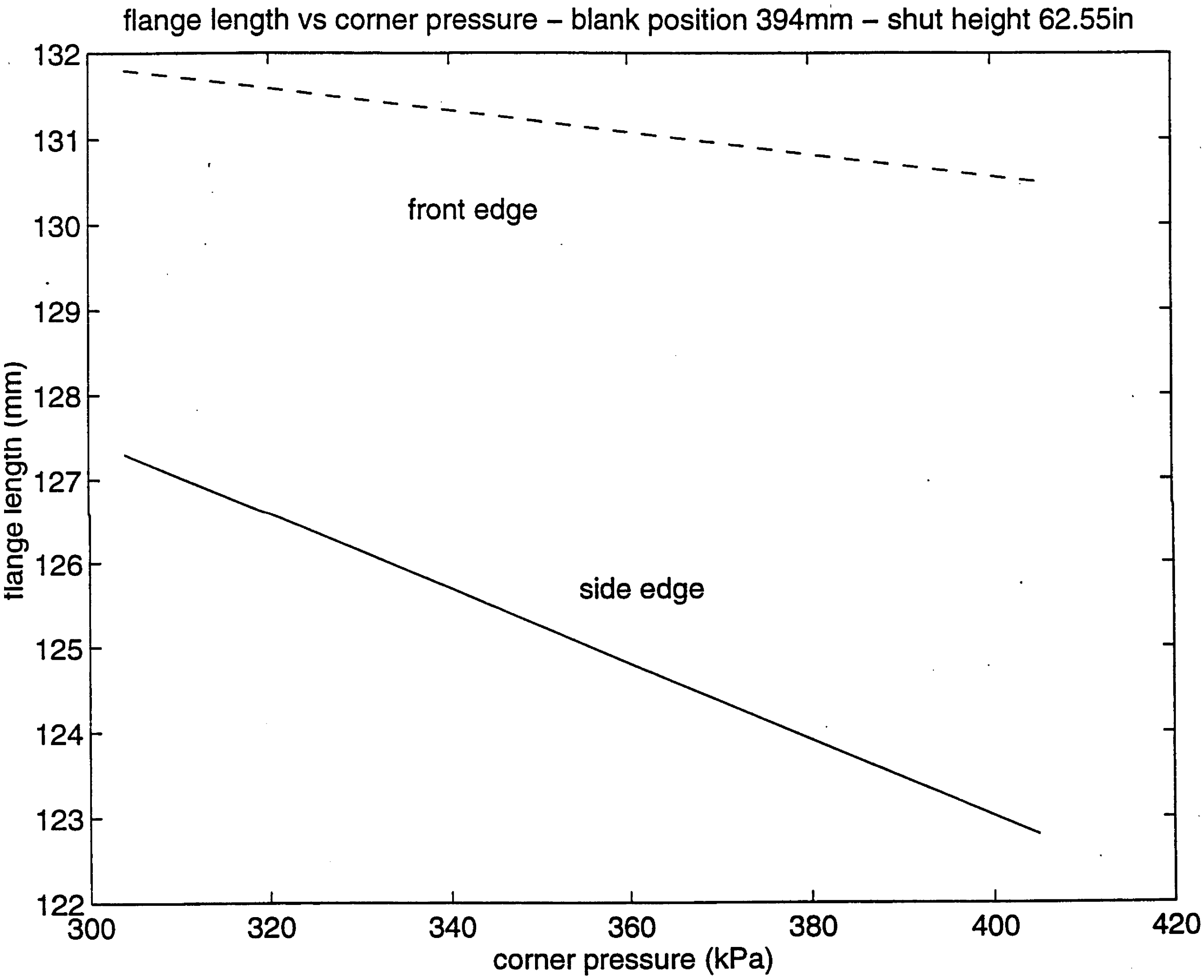


flange length vs corner pressure – blank position 394mm – shut height 62.537in
flange length (mm)
138
137
136
135
134
133
132
131
130
129
300
320
340
360
380
400
420
corner pressure (kPa)
side edge
front edge

Graph No.19

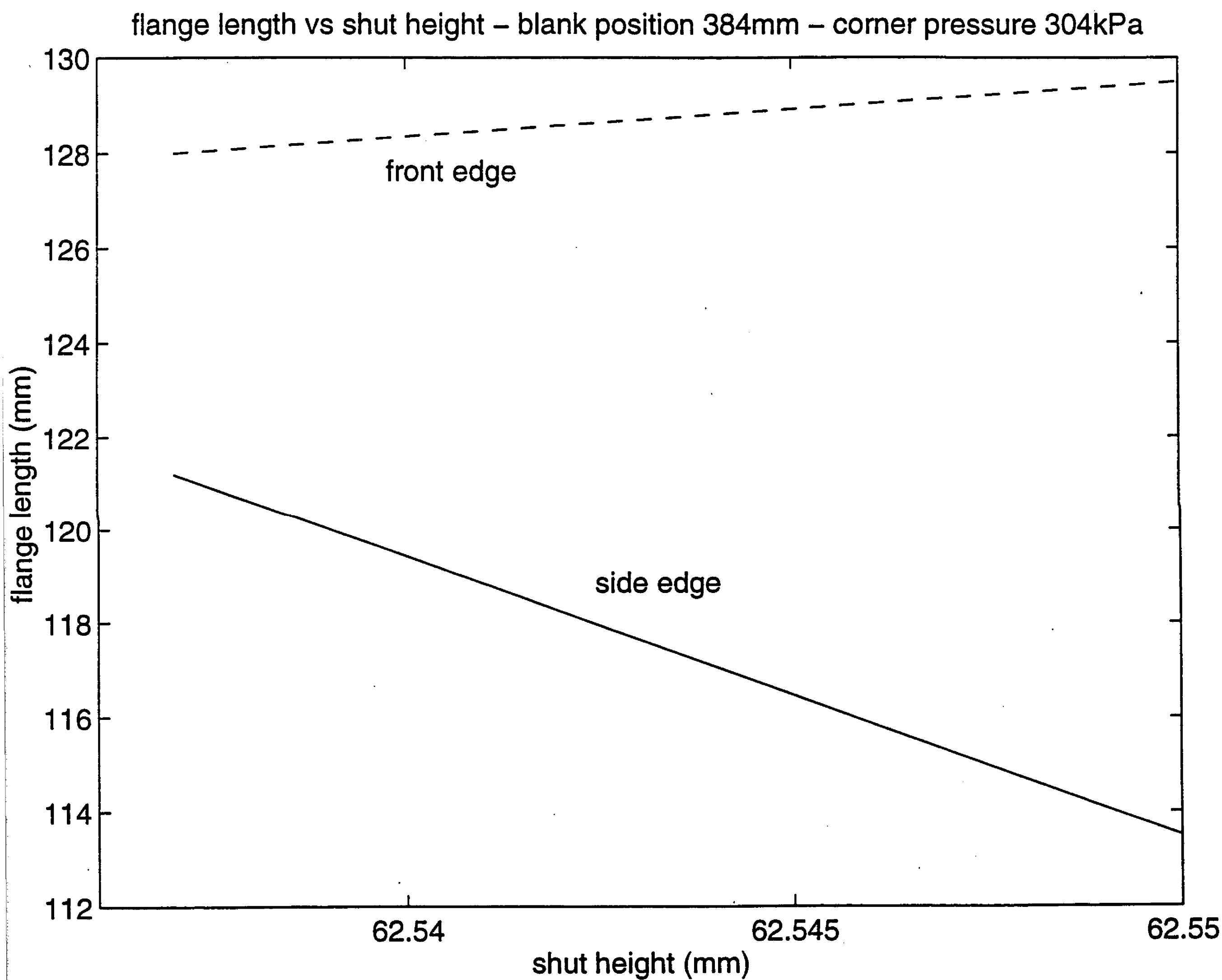

flange length vs corner pressure – blank position 384mm – shut height 62.55in
front edge
side edge
flange length (mm)
corner pressure (kPa)
130
128
126
124
122
120
118
116
114
112
300
320
340
360
380
400
420

Graph No.20



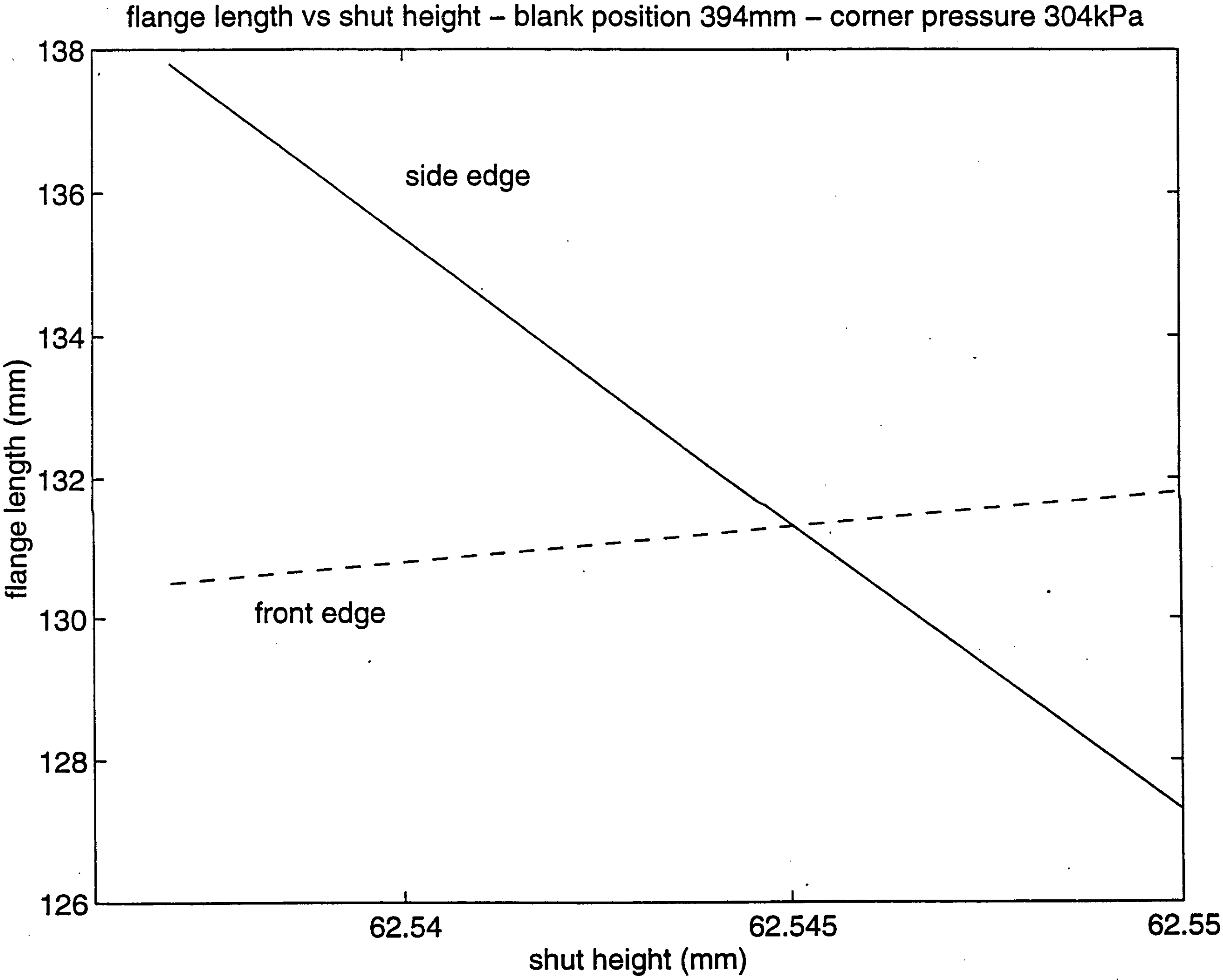
flange length vs corner pressure – blank position 394mm – shut height 62.55in
front edge
side edge
flange length (mm)
corner pressure (kPa)
132
131
130
129
128
127
126
125
124
123
122
300
320
340
360
380
400
420

Graph No.21

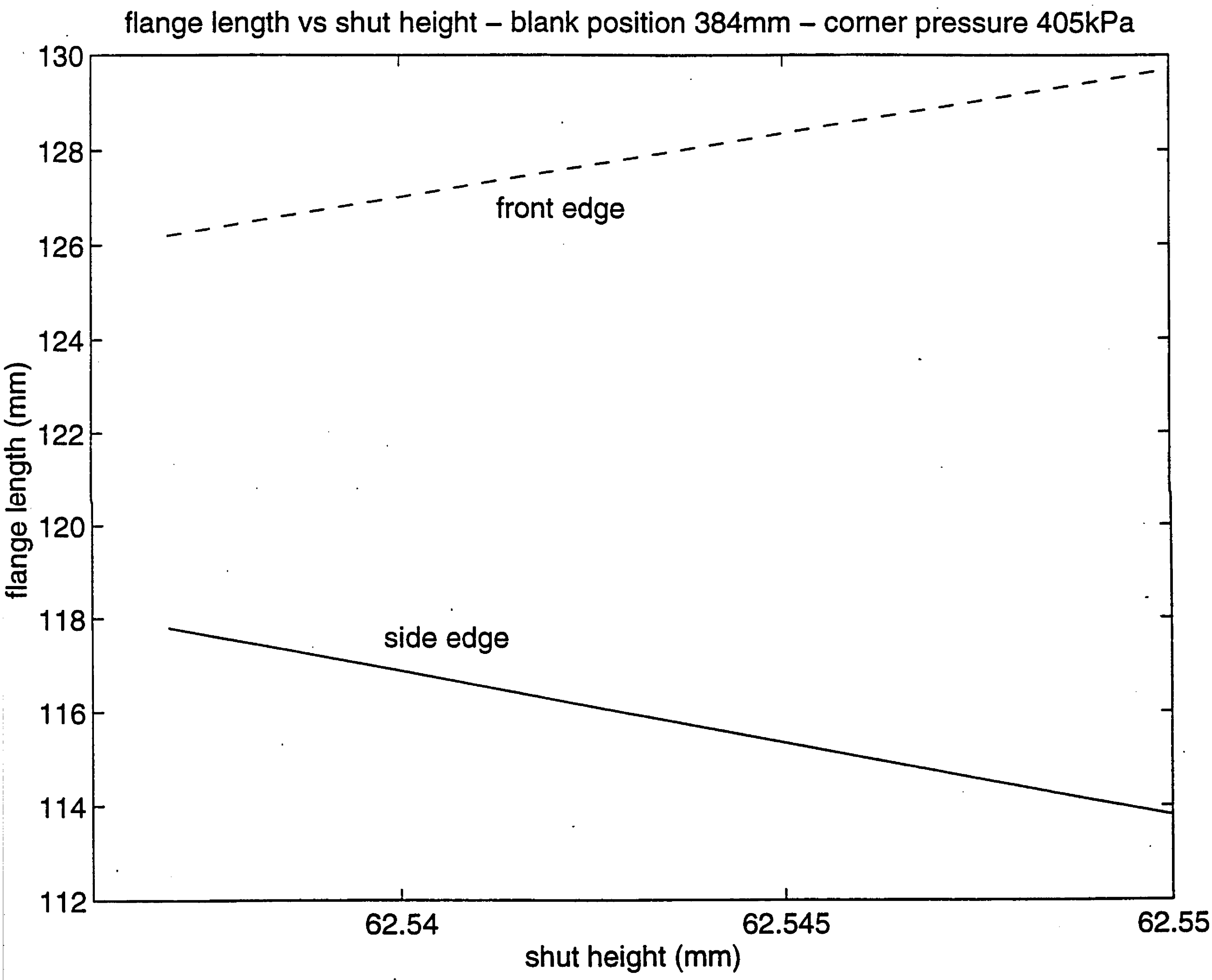


flange length vs shut height – blank position 384mm – corner pressure 304kPa
130
128
126
124
122
120
118
116
114
112
flange length (mm)
front edge
side edge
62.54
62.545
62.55
shut height (mm)

Graph No.22

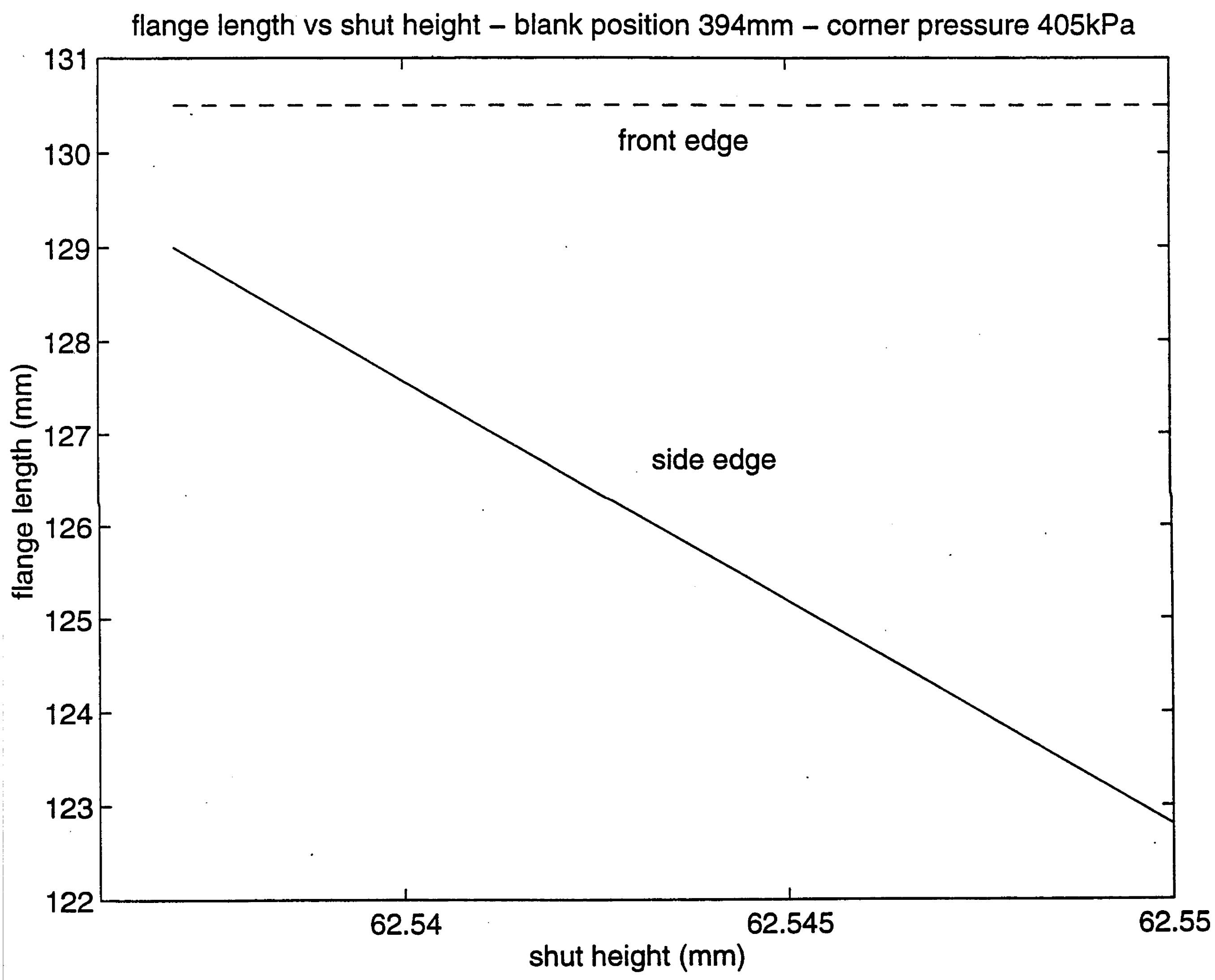

flange length vs shut height – blank position 394mm – corner pressure 304kPa
138
136
134
132
130
128
126
flange length (mm)
side edge
front edge
62.54
62.545
62.55
shut height (mm)

Graph No.23



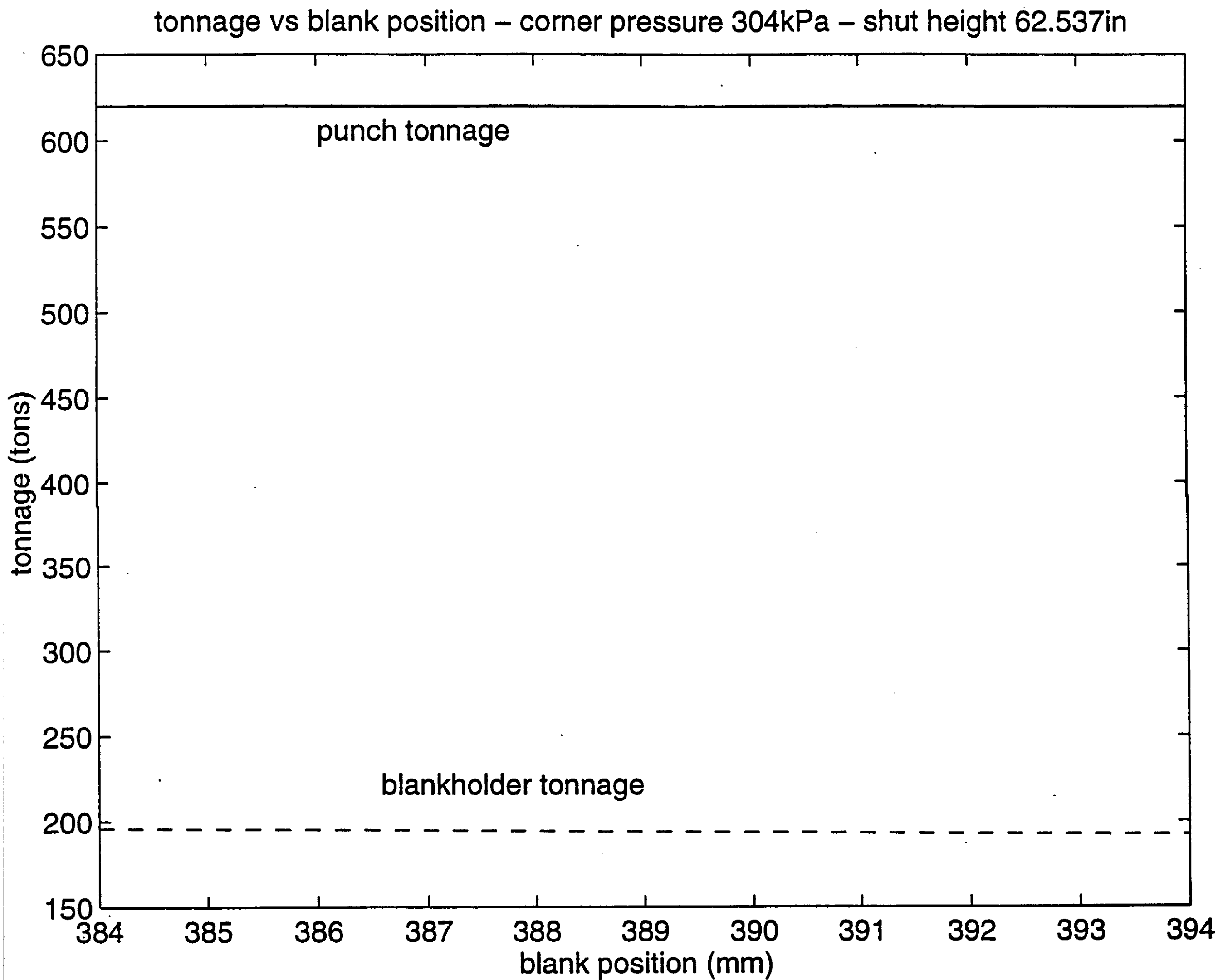
flange length vs shut height – blank position 384mm – corner pressure 405kPa
130
128
126
124
122
120
118
116
114
112
flange length (mm)
front edge
side edge
62.54
62.545
62.55
shut height (mm)

Graph No.24

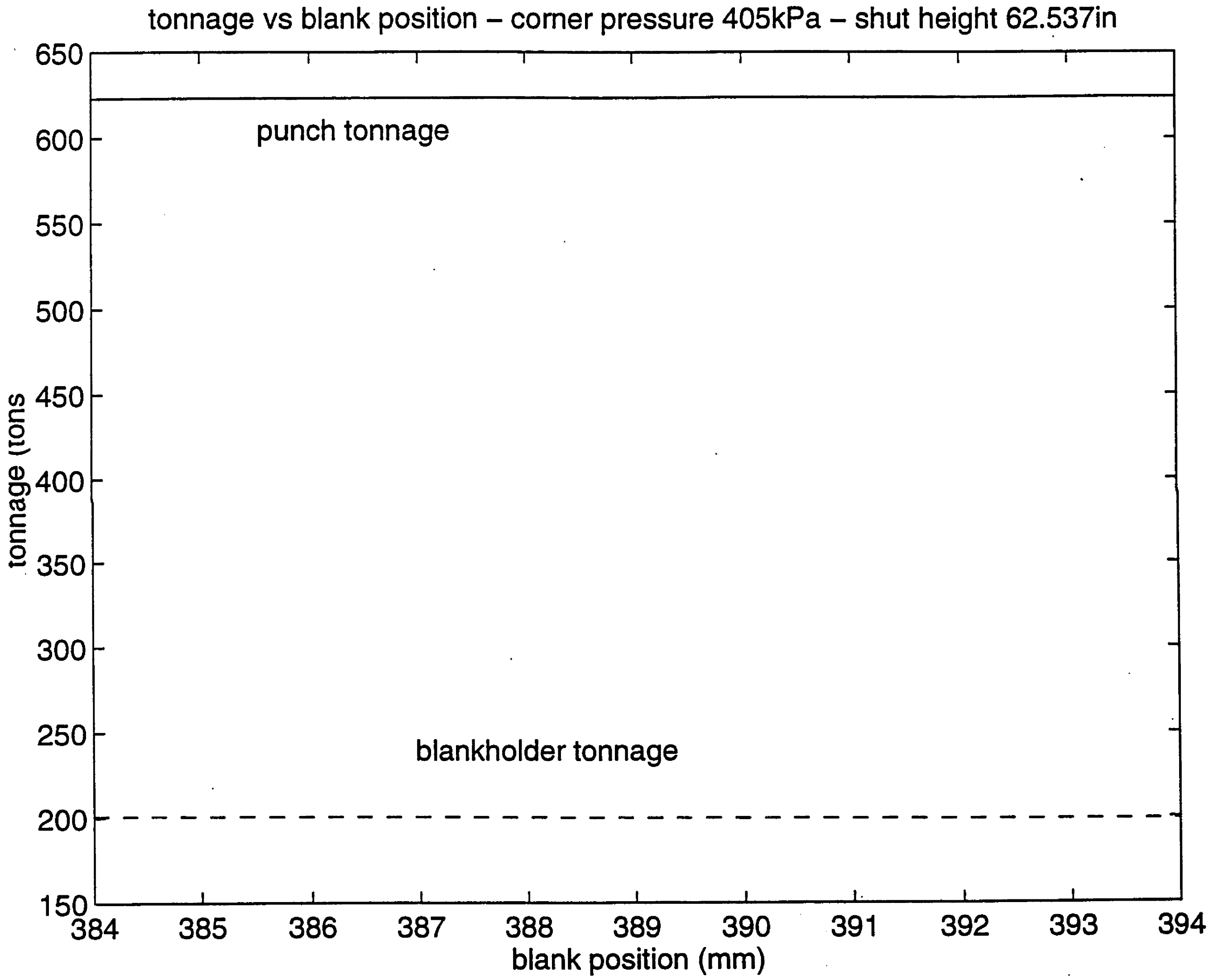


flange length vs shut height – blank position 394mm – corner pressure 405kPa
131
130
129
128
127
126
125
124
123
122
flange length (mm)
front edge
side edge
62.54
62.545
62.55
shut height (mm)

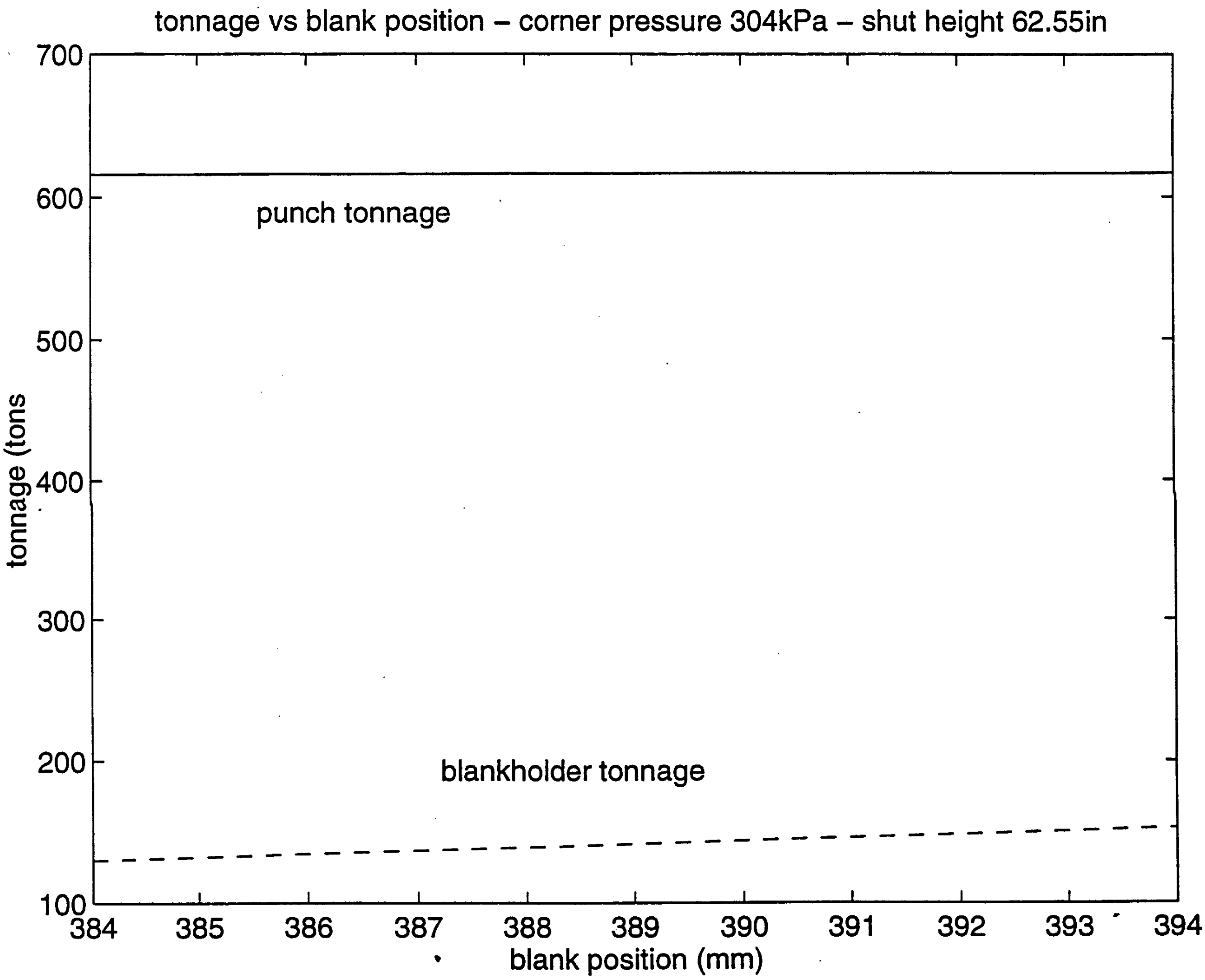
Graph No.25


tonnage vs blank position – corner pressure 304kPa – shut height 62.537in
punch tonnage
blankholder tonnage
tonnage (tons)
650
600
550
500
450
400
350
300
250
200
150
384
385
386
387
388
389
390
391
392
393
394
blank position (mm)

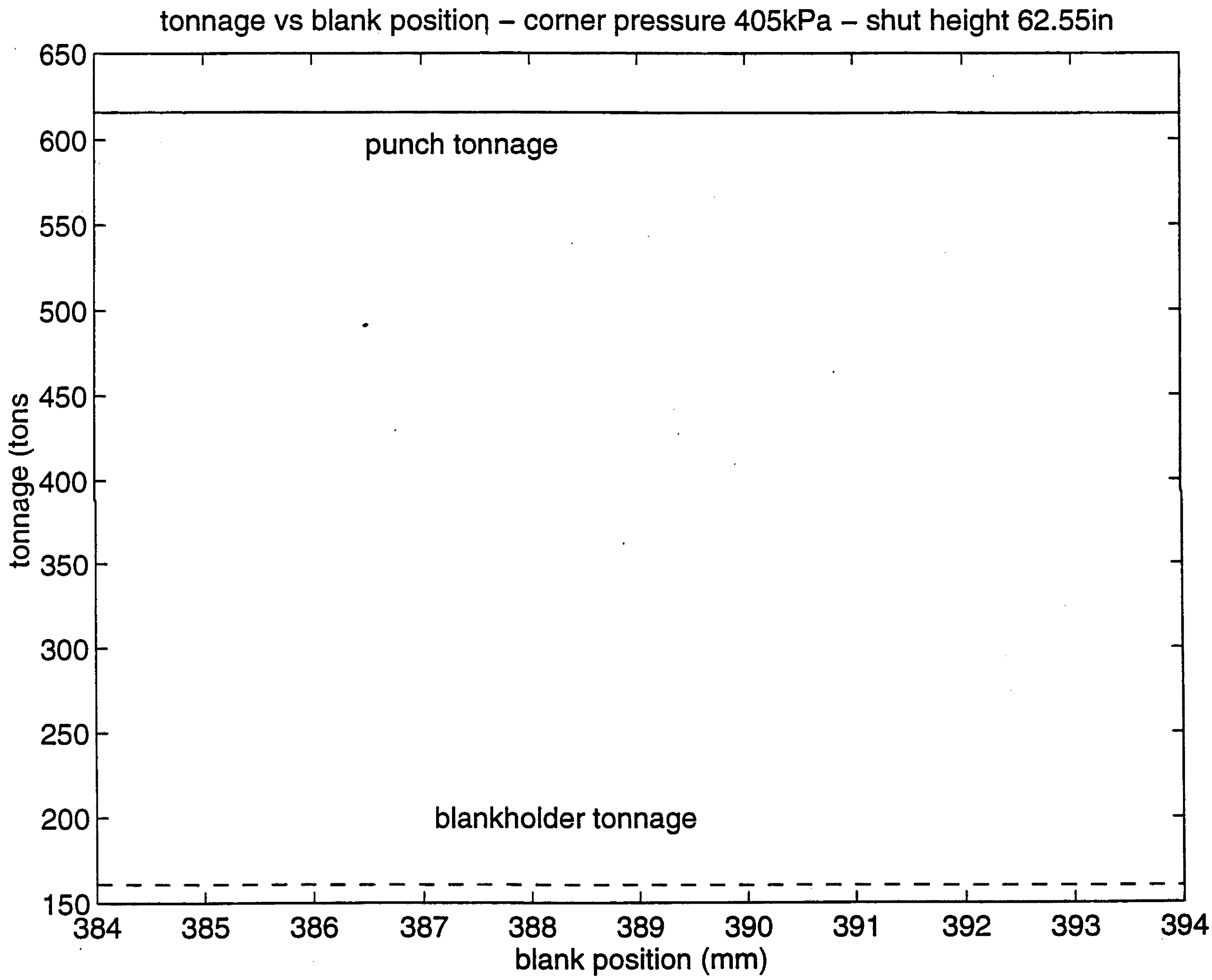
Graph No.26


tonnage vs blank position – corner pressure 405kPa – shut height 62.537in
650
600
550
500
450
400
350
300
250
200
150
tonnage (tons
punch tonnage
blankholder tonnage
384
385
386
387
388
389
390
391
392
393
394
blank position (mm)

Graph No.27

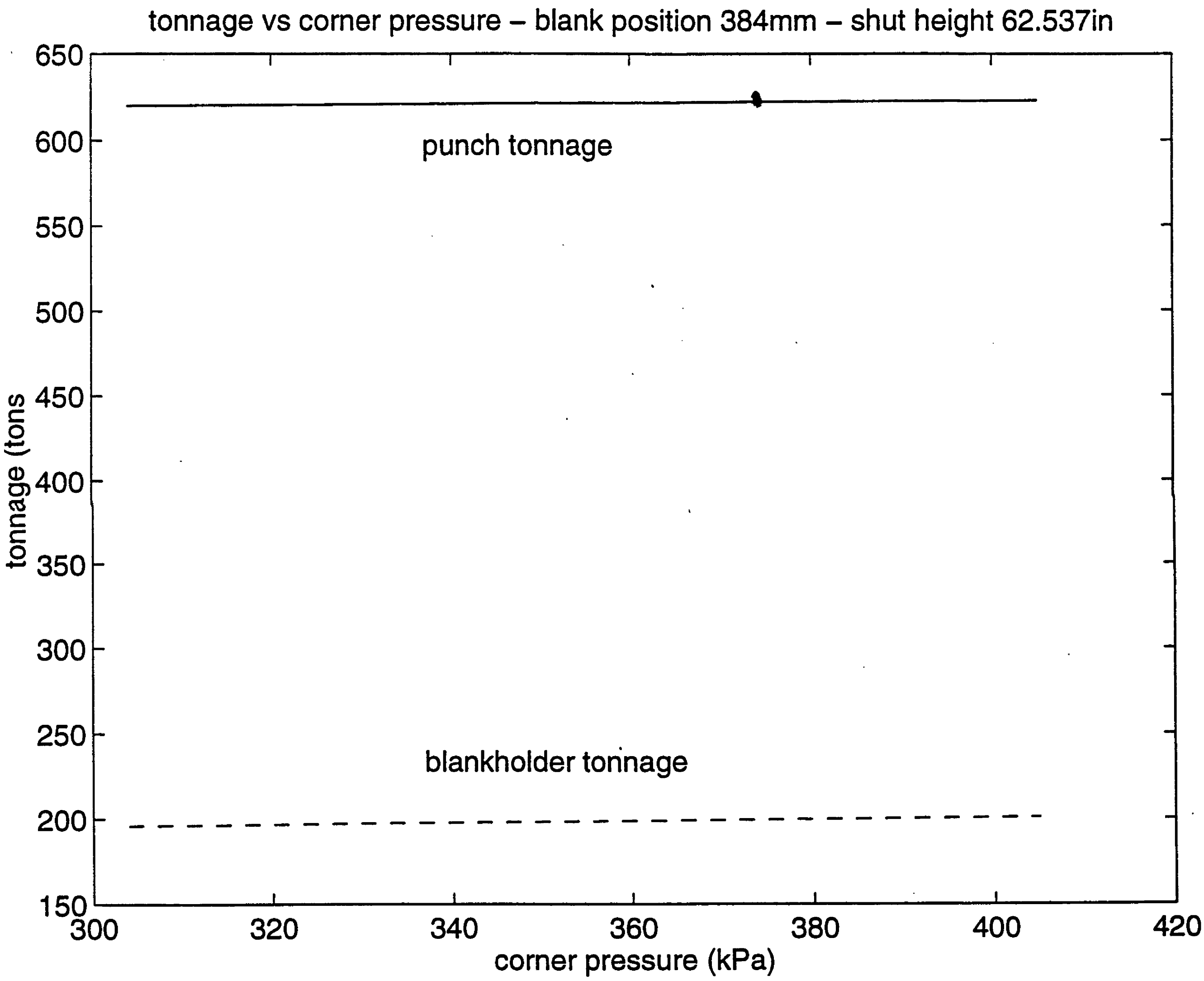

tonnage vs blank position – corner pressure 304kPa – shut height 62.55in
700
600
500
400
300
200
100
tonnage (tons
punch tonnage
blankholder tonnage
384
385
386
387
388
389
390
391
392
393
394
blank position (mm)

Graph No.28



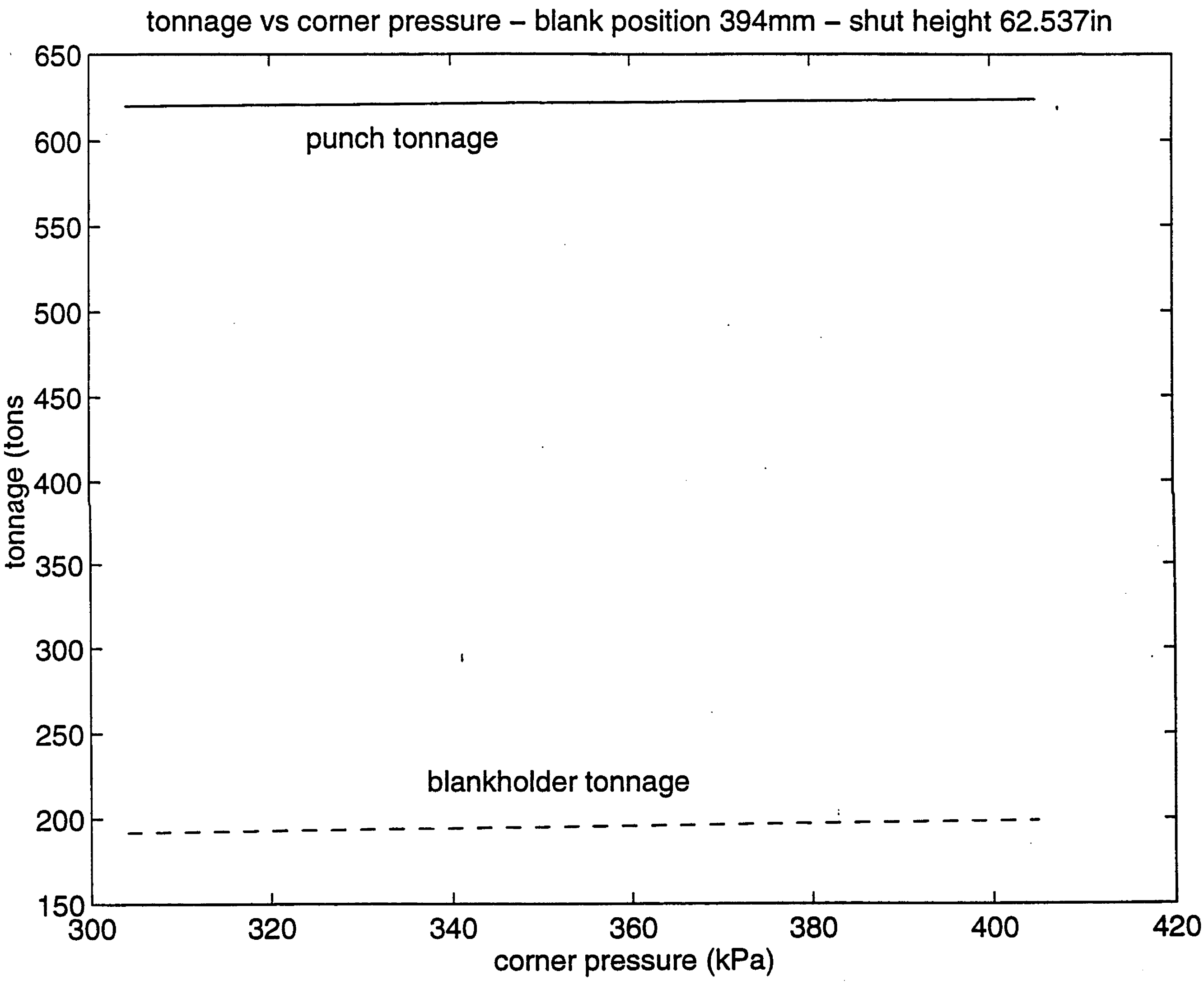
tonnage vs blank position - corner pressure 405kPa - shut height 62.55in
punch tonnage
blankholder tonnage
tonnage (tons
blank position (mm)
650
600
550
500
450
400
350
300
250
200
150
384
385
386
387
388
389
390
391
392
393
394

Graph No.29



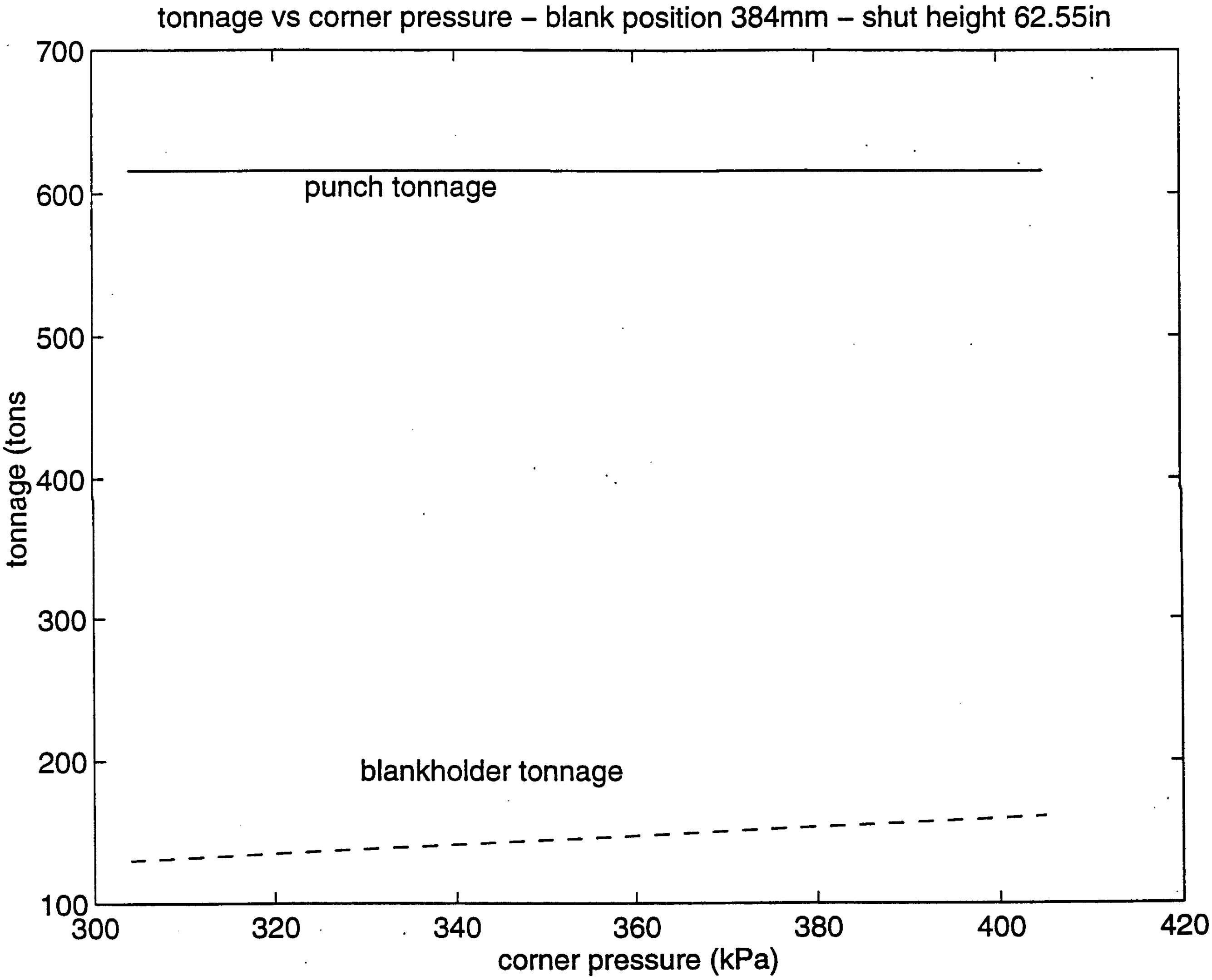
tonnage vs corner pressure – blank position 384mm – shut height 62.537in
650
600
550
500
450
400
350
300
250
200
150
tonnage (tons
punch tonnage
blankholder tonnage
300
320
340
360
380
400
420
corner pressure (kPa)

Graph No.30



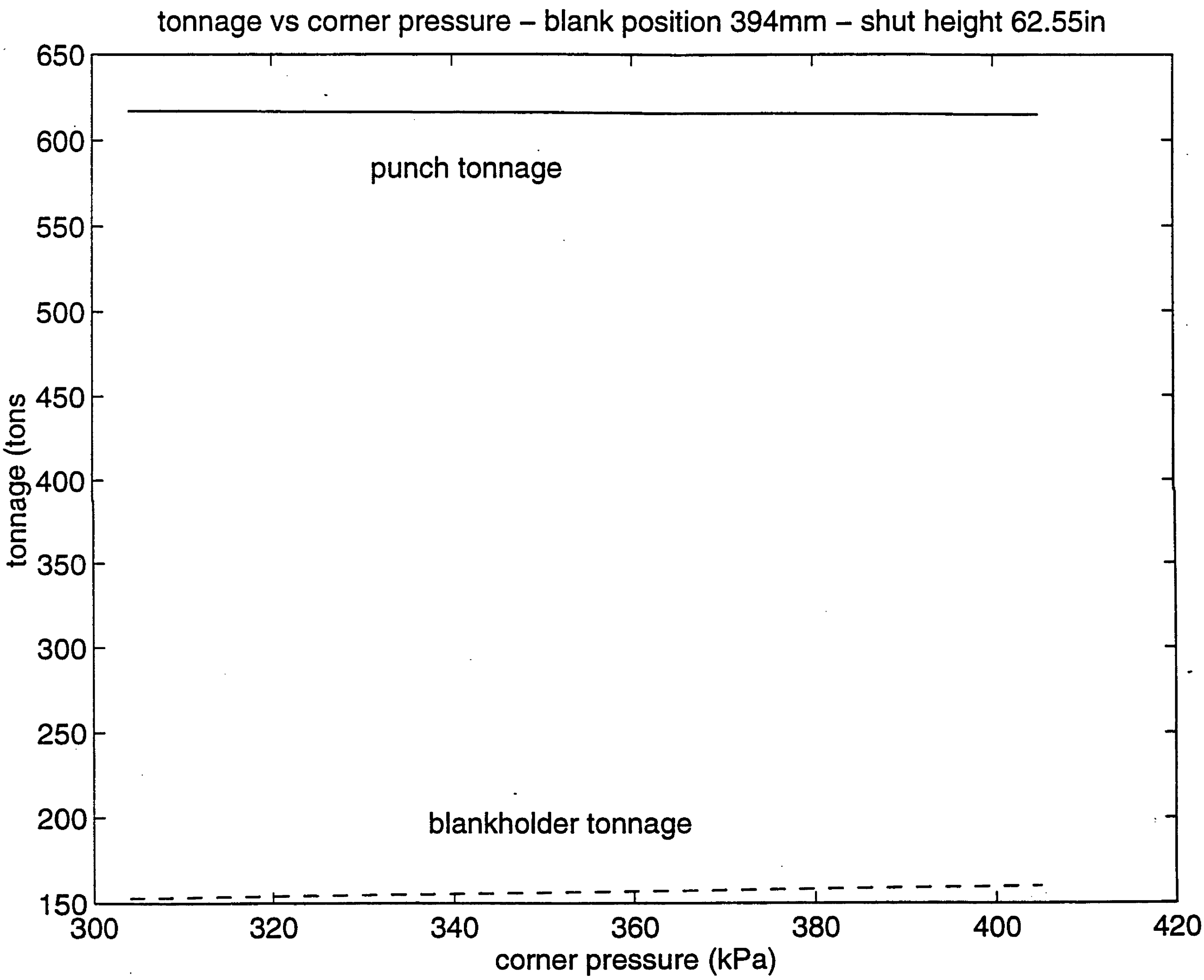
tonnage vs corner pressure – blank position 394mm – shut height 62.537in
650
600
550
500
450
400
350
300
250
200
150
tonnage (tons
300
320
340
360
380
400
420
corner pressure (kPa)
punch tonnage
blankholder tonnage

Graph No.31

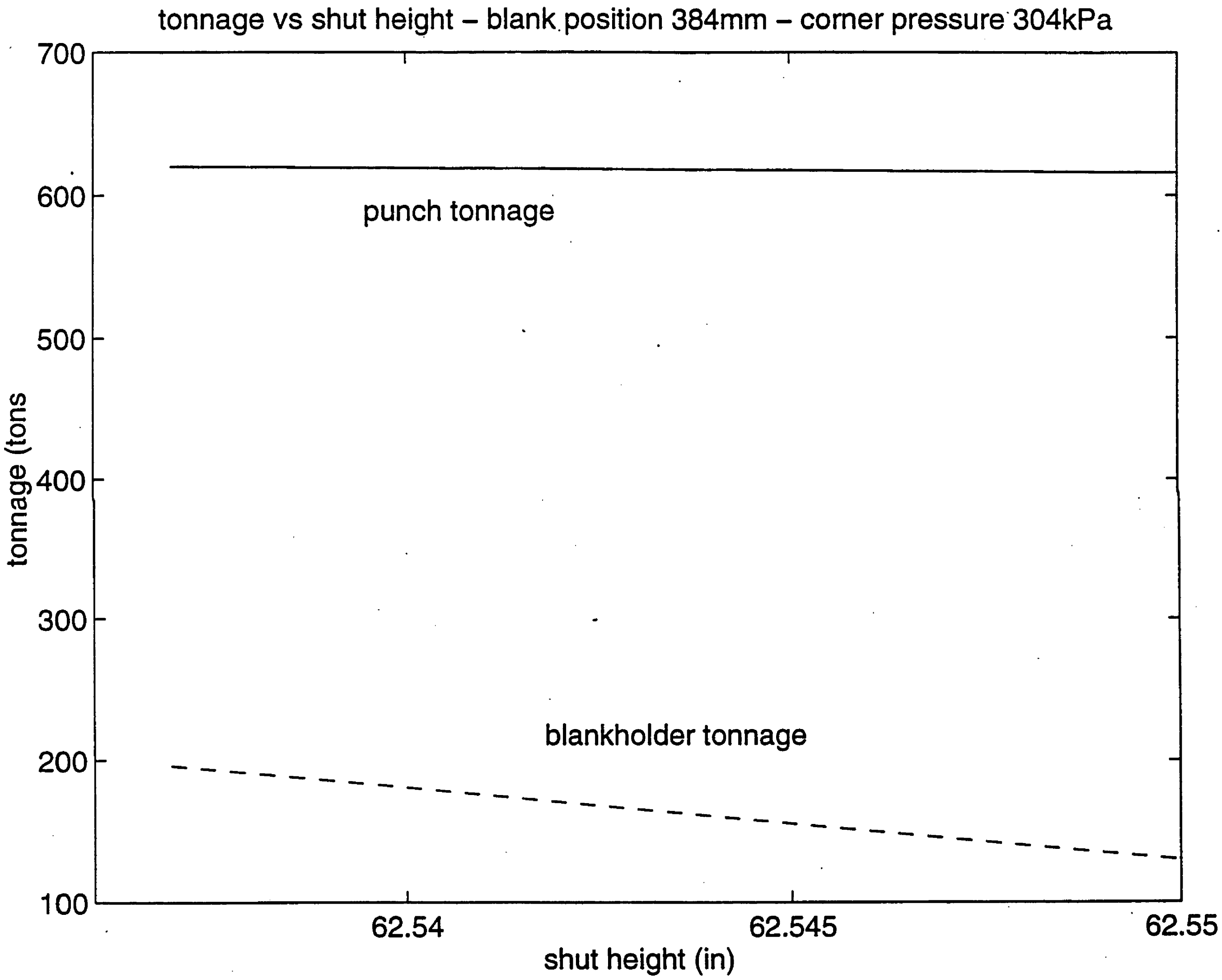


tonnage vs corner pressure – blank position 384mm – shut height 62.55in
punch tonnage
blankholder tonnage
tonnage (tons
corner pressure (kPa)
700
600
500
400
300
200
100
300
320
340
360
380
400
420

Graph No.32

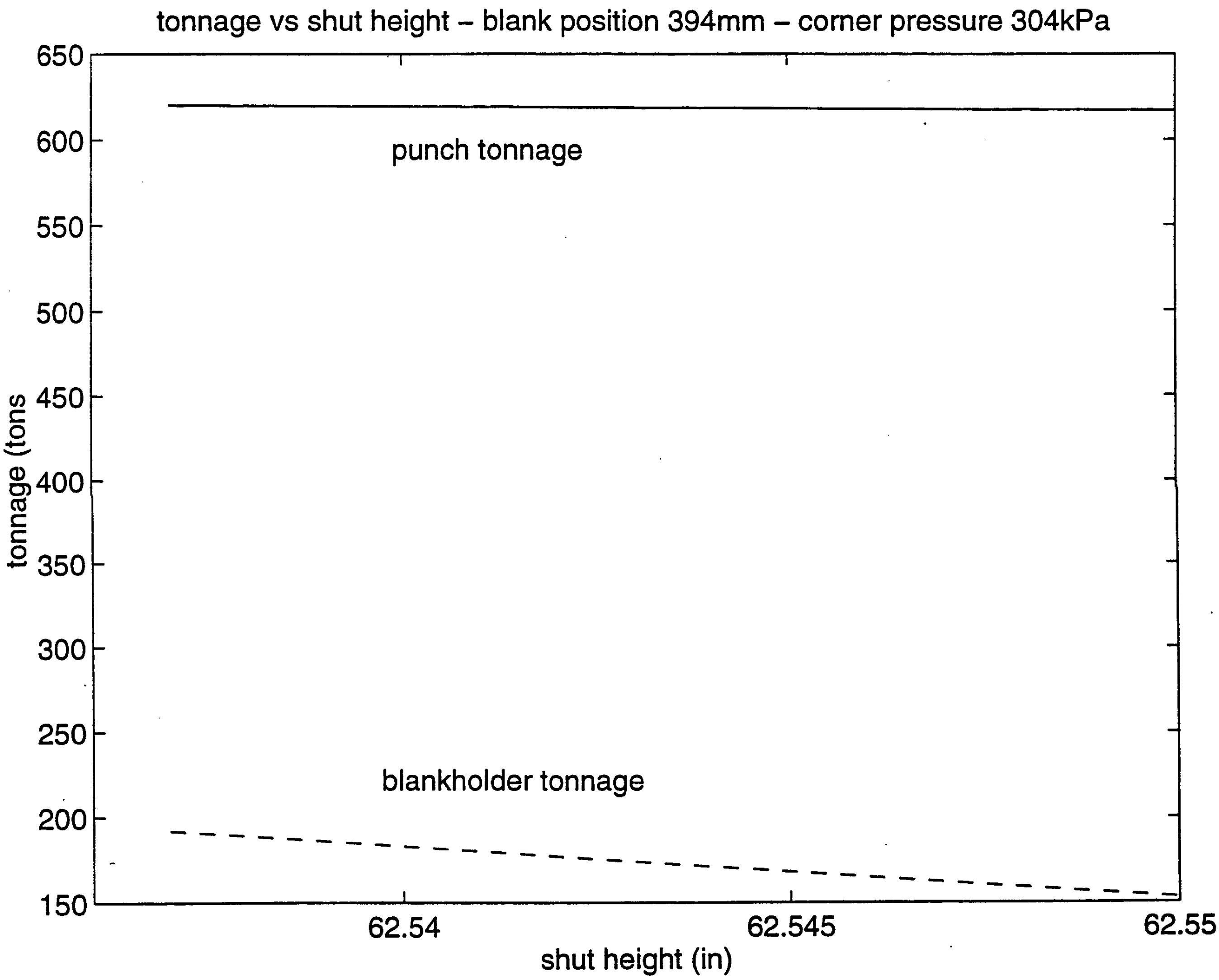

tonnage vs corner pressure – blank position 394mm – shut height 62.55in
650
600
550
500
450
400
350
300
250
200
150
tonnage (tons
punch tonnage
blankholder tonnage
300
320
340
360
380
400
420
corner pressure (kPa)

Graph No.33



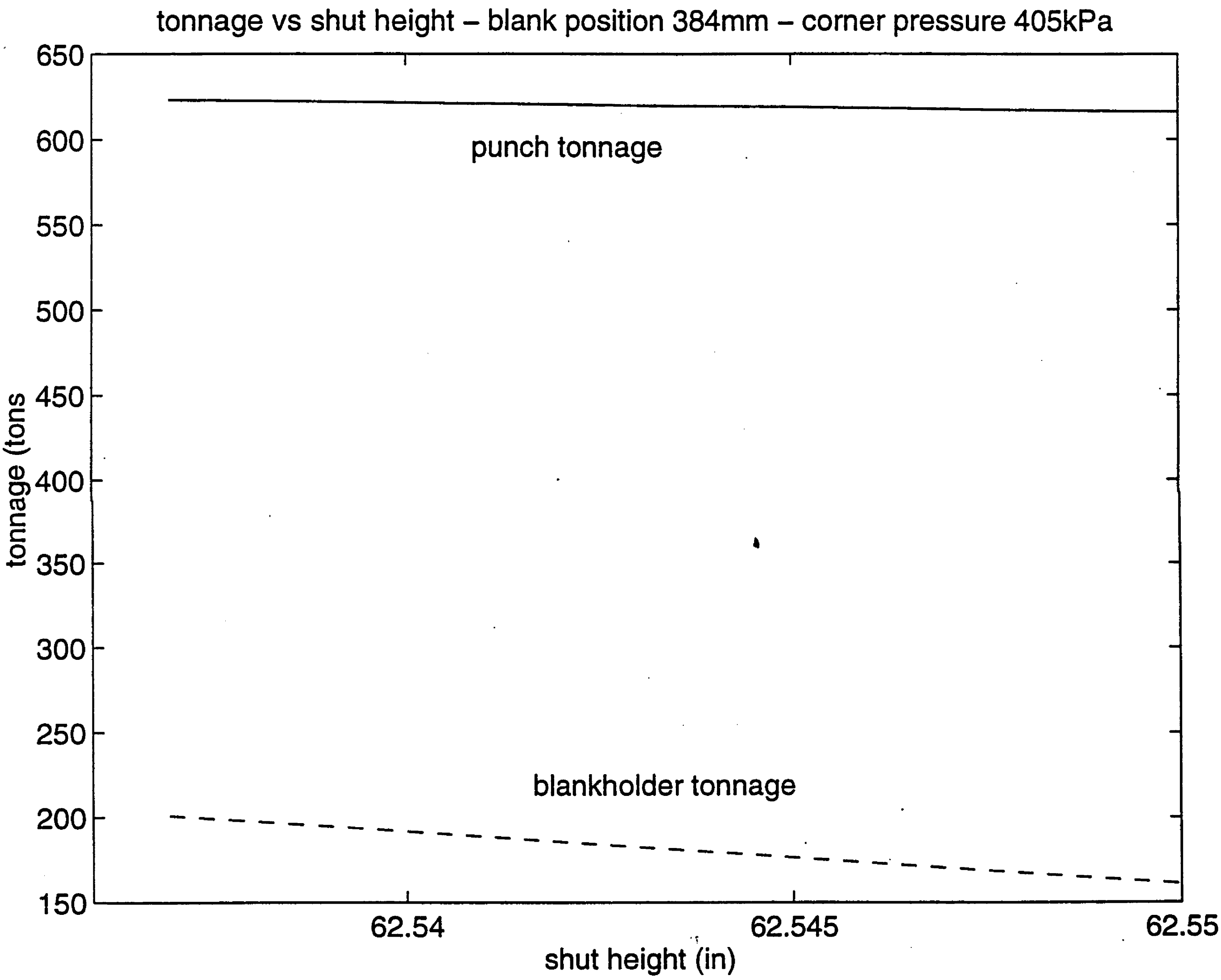
tonnage vs shut height – blank position 384mm – corner pressure 304kPa
700
600
500
400
300
200
100
tonnage (tons
punch tonnage
blankholder tonnage
62.54
62.545
62.55
shut height (in)

Graph No.34



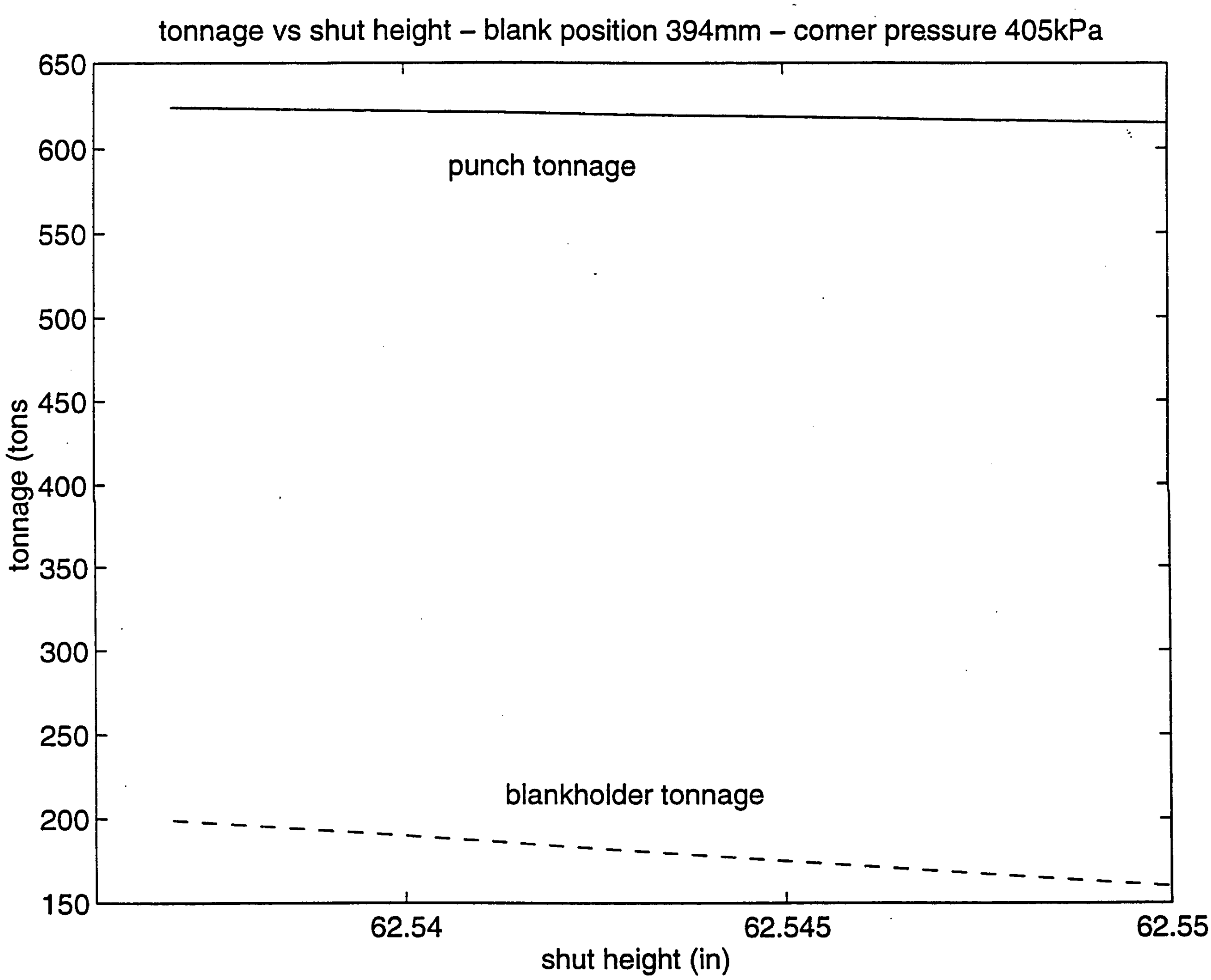
tonnage vs shut height – blank position 394mm – corner pressure 304kPa
650
600
550
500
450
400
350
300
250
200
150
tonnage (tons
punch tonnage
blankholder tonnage
62.54
62.545
62.55
shut height (in)

Graph No.35



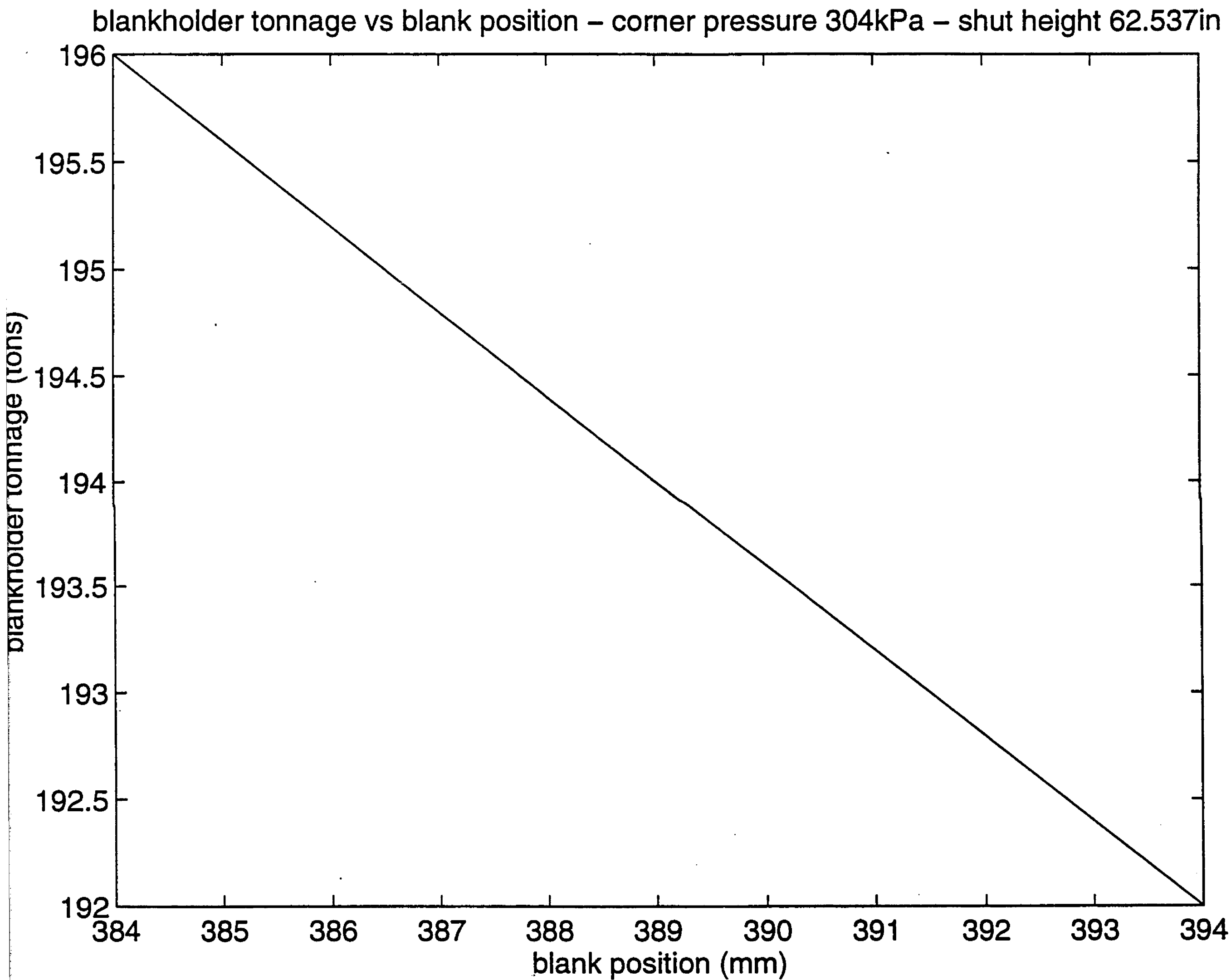
tonnage vs shut height - blank position 384mm - corner pressure 405kPa
650
600
550
500
450
400
350
300
250
200
150
tonnage (tons
punch tonnage
blankholder tonnage
62.54
62.545
62.55
shut height (in)

Graph No.36



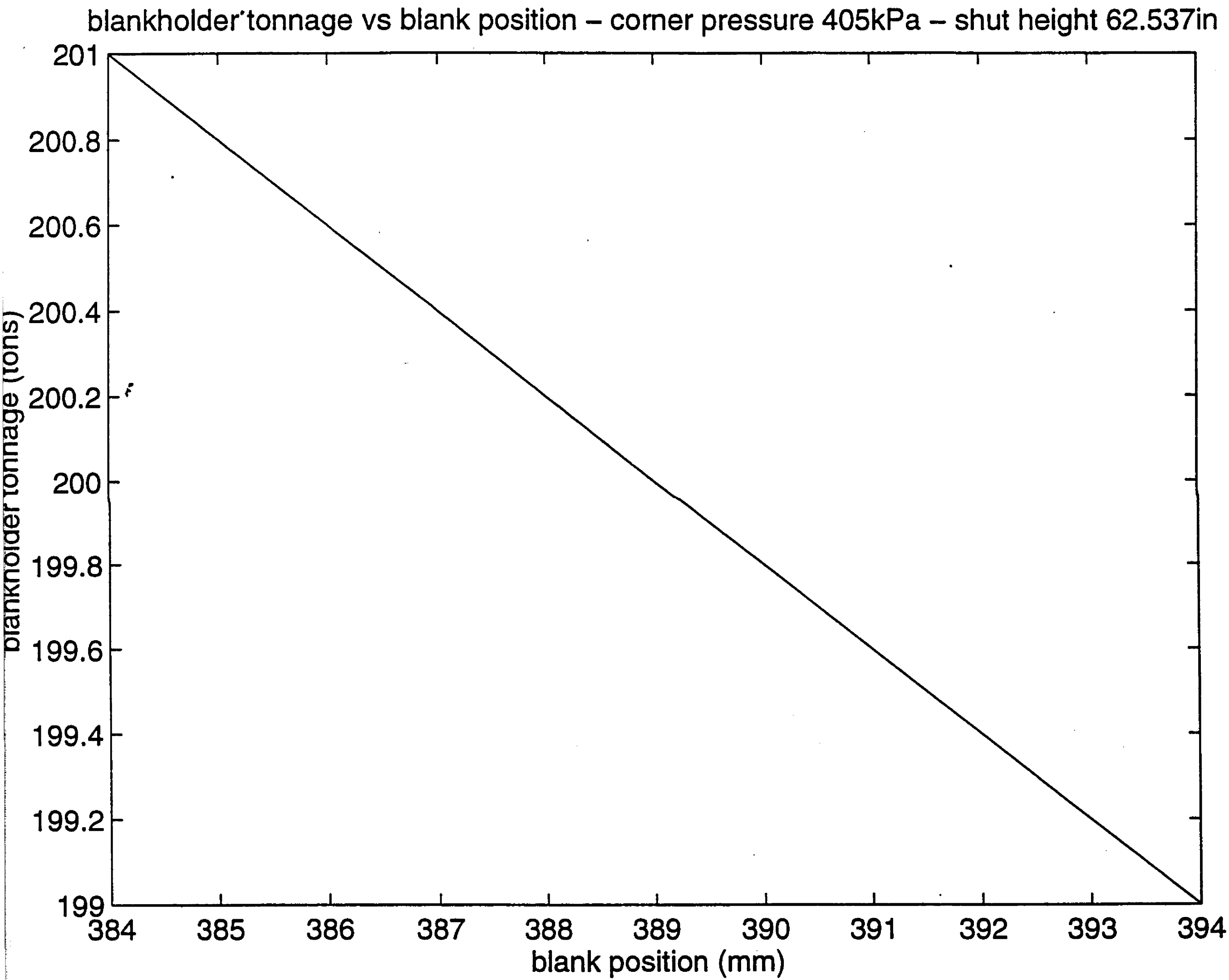
tonnage vs shut height – blank position 394mm – corner pressure 405kPa
650
600
550
500
450
400
350
300
250
200
150
tonnage (tons
punch tonnage
blankholder tonnage
62.54
62.545
62.55
shut height (in)

Graph No.37



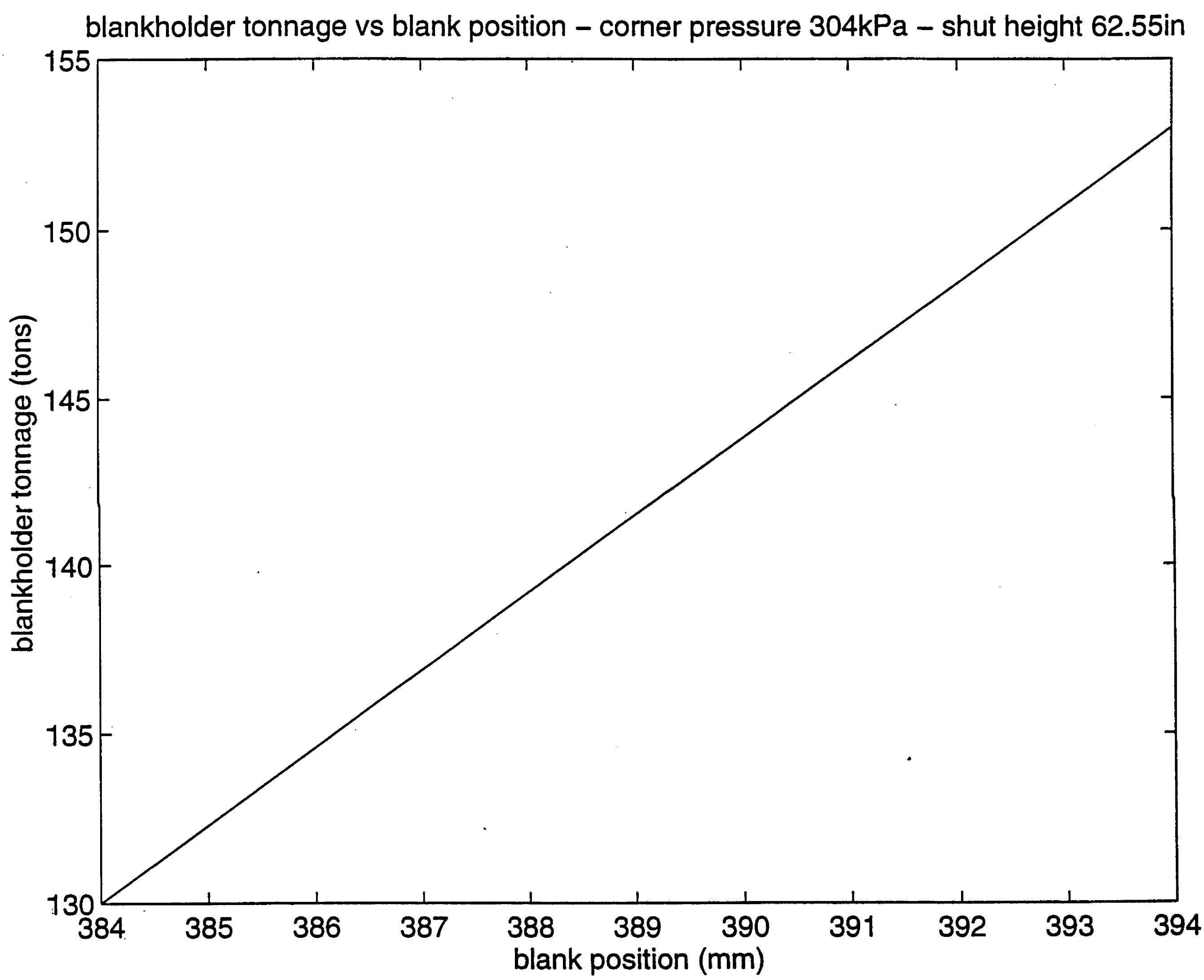
blankholder tonnage vs blank position – corner pressure 304kPa – shut height 62.537in
blankholder tonnage (tons)
196
195.5
195
194.5
194
193.5
193
192.5
192
384
385
386
387
388
389
390
391
392
393
394
blank position (mm)

Graph No.38

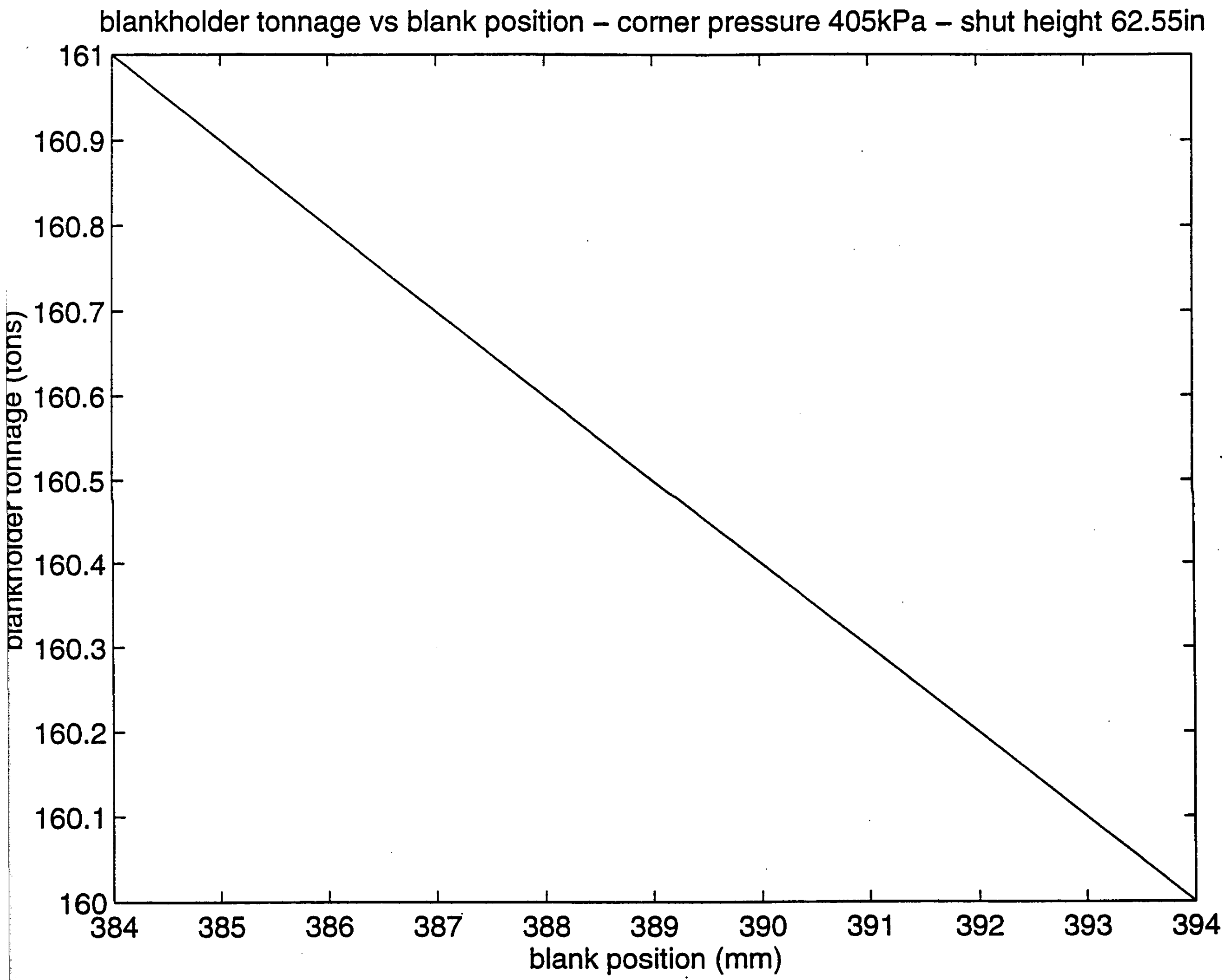


blankholder tonnage vs blank position – corner pressure 405kPa – shut height 62.537in
blankholder tonnage (tons)
201
200.8
200.6
200.4
200.2
200
199.8
199.6
199.4
199.2
199
384
385
386
387
388
389
390
391
392
393
394
blank position (mm)

Graph No.39

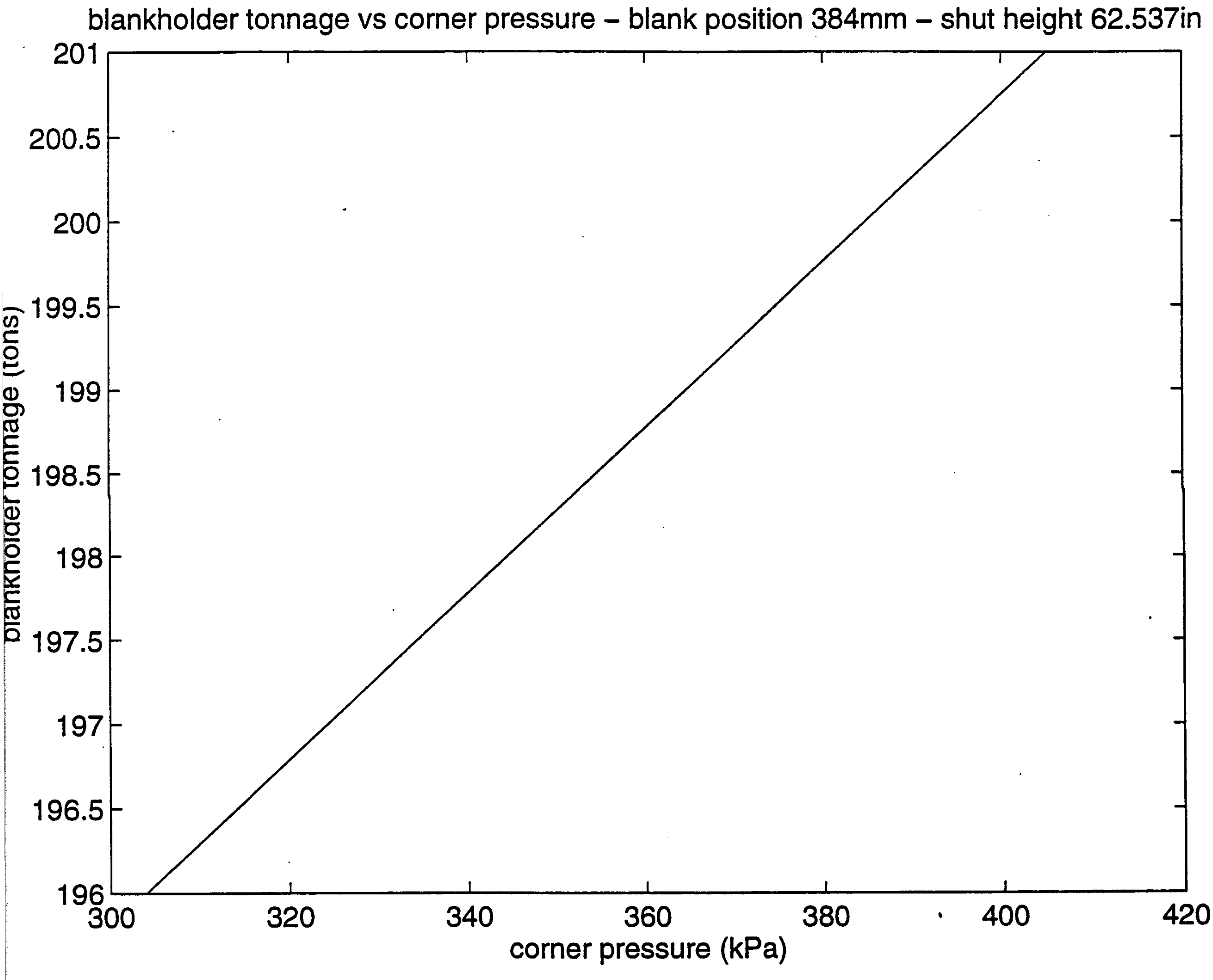

blankholder tonnage vs blank position – corner pressure 304kPa – shut height 62.55in
155
150
145
140
135
130
blankholder tonnage (tons)
384
385
386
387
388
389
390
391
392
393
394
blank position (mm)

Graph No.40



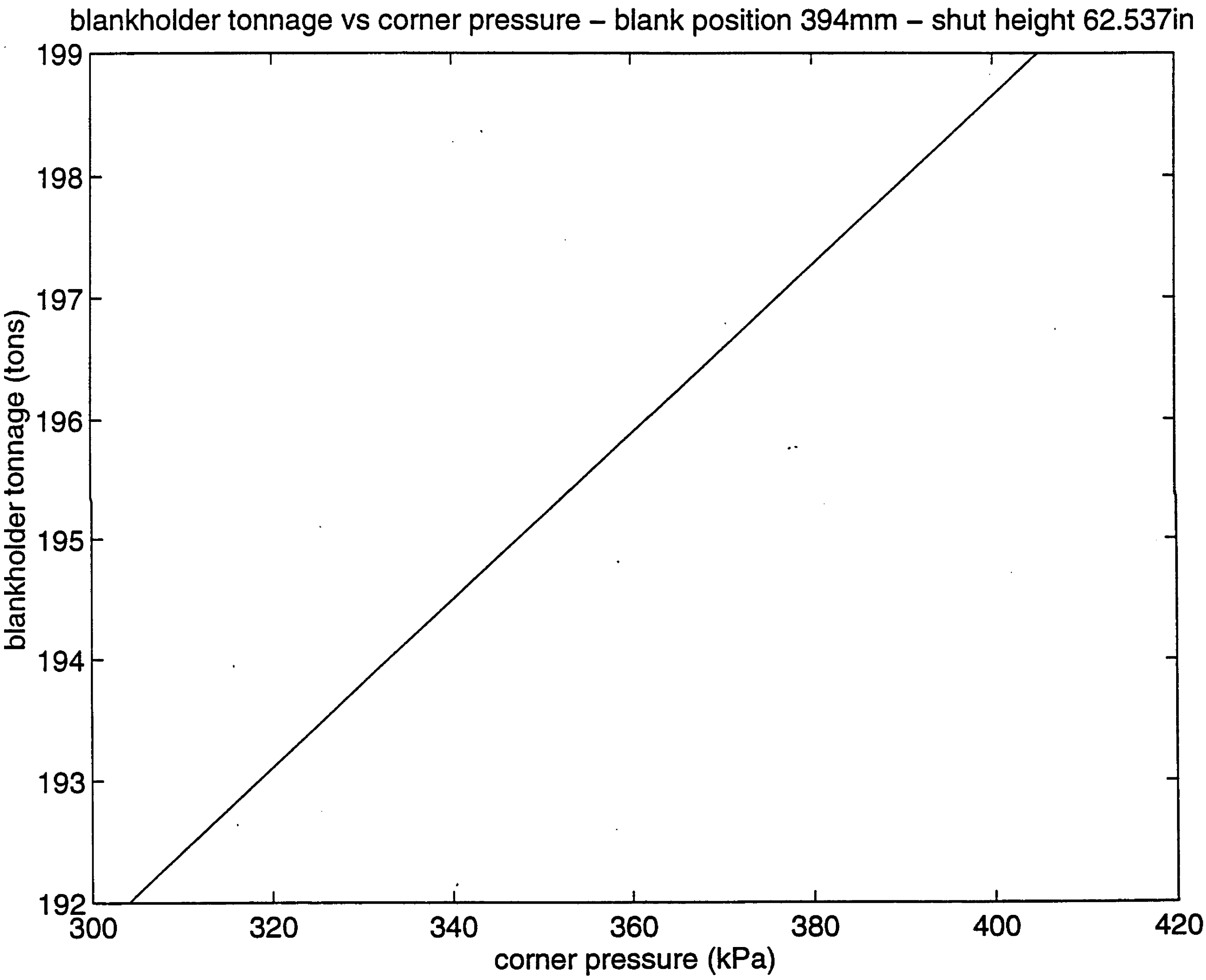
blankholder tonnage vs blank position – corner pressure 405kPa – shut height 62.55in
161
160.9
160.8
160.7
160.6
160.5
160.4
160.3
160.2
160.1
160
blankholder tonnage (tons)
384
385
386
387
388
389
390
391
392
393
394
blank position (mm)

Graph No.41

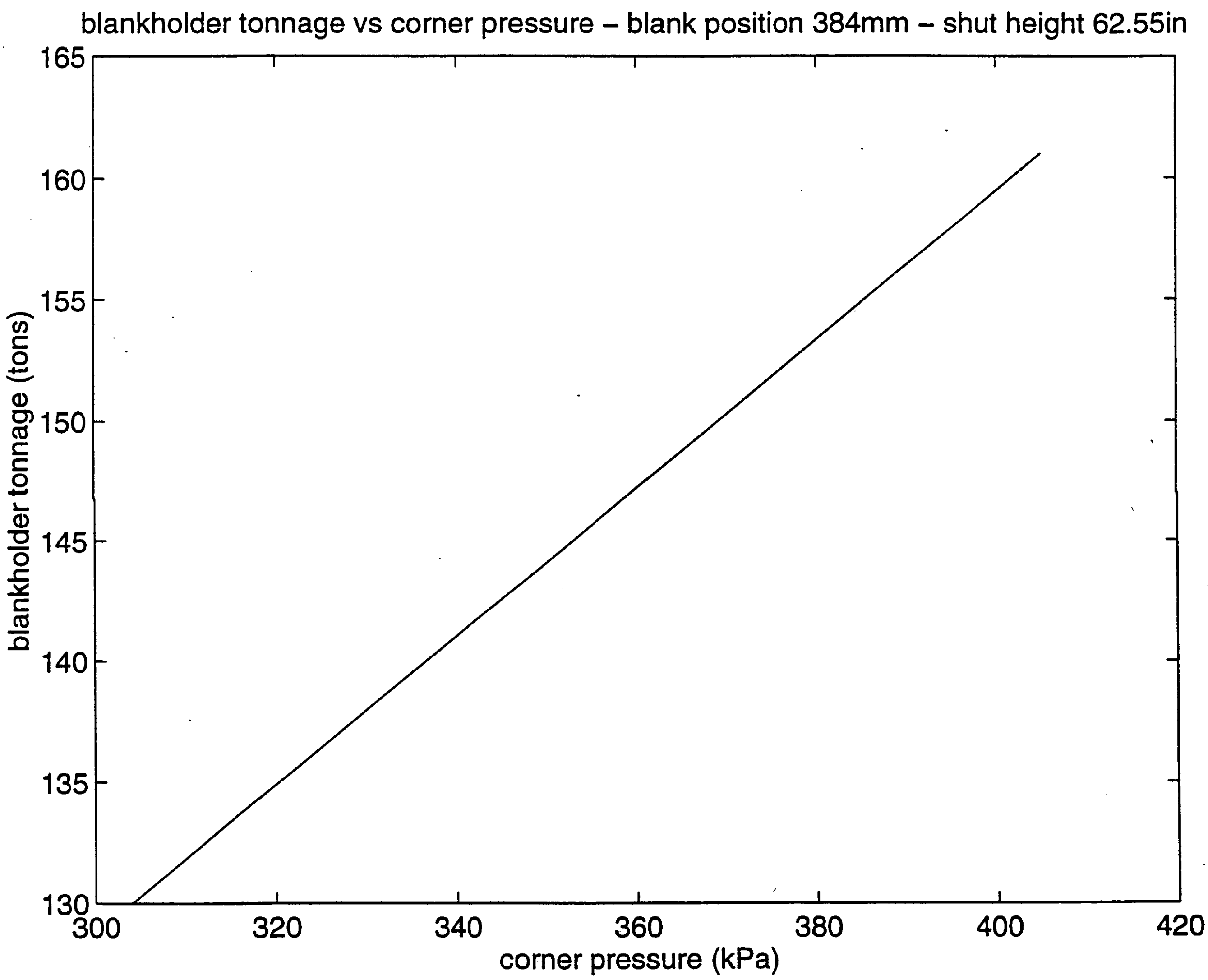


blankholder tonnage vs corner pressure - blank position 384mm - shut height 62.537in
blankholder tonnage (tons)
201
200.5
200
199.5
199
198.5
198
197.5
197
196.5
196
300
320
340
360
380
400
420
corner pressure (kPa)

Graph No.42

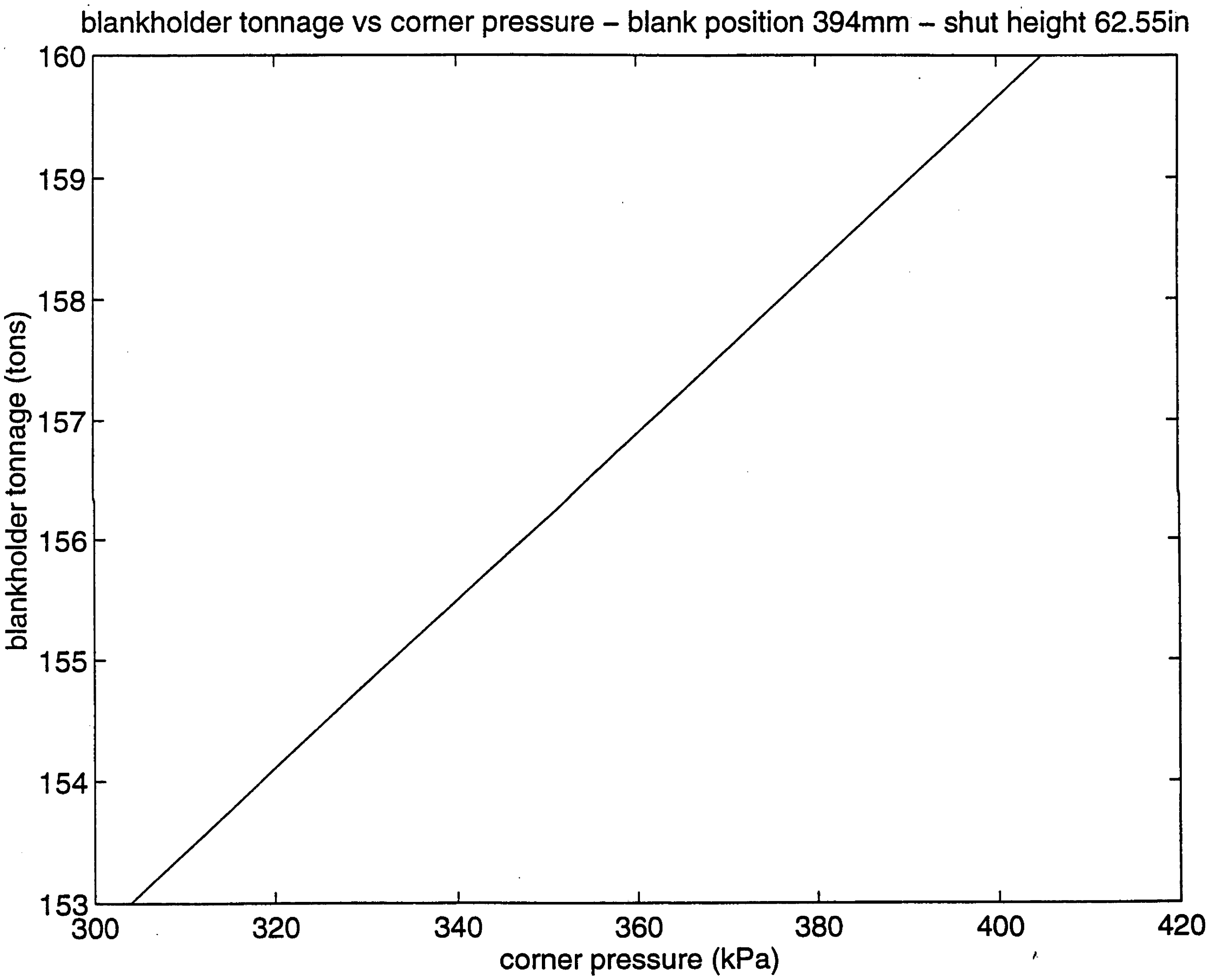

blankholder tonnage vs corner pressure – blank position 394mm – shut height 62.537in
199
198
197
196
195
194
193
192
blankholder tonnage (tons)
300
320
340
360
380
400
420
corner pressure (kPa)

Graph No.43

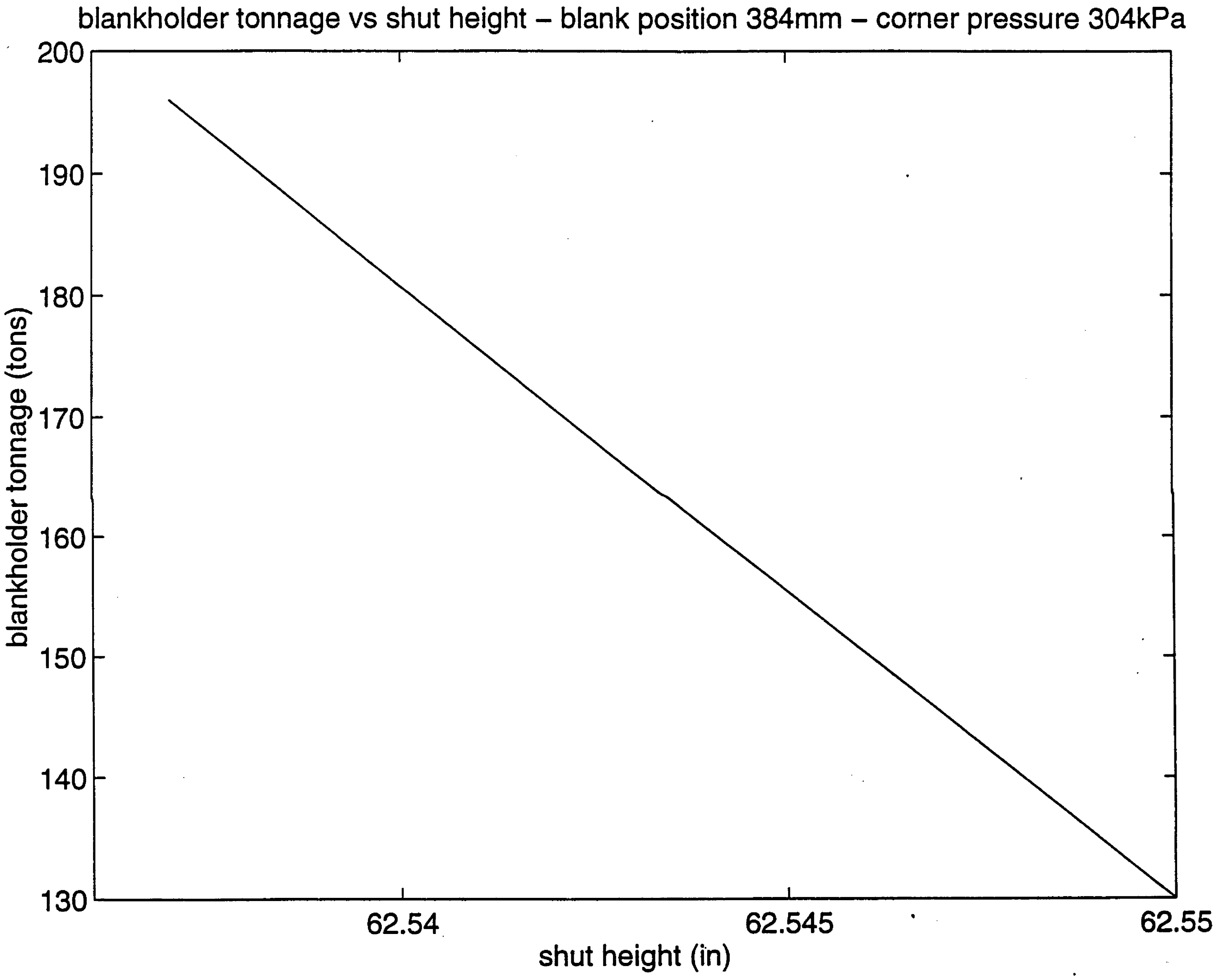


blankholder tonnage vs corner pressure – blank position 384mm – shut height 62.55in
165
160
155
150
145
140
135
130
blankholder tonnage (tons)
300
320
340
360
380
400
420
corner pressure (kPa)

Graph No.44

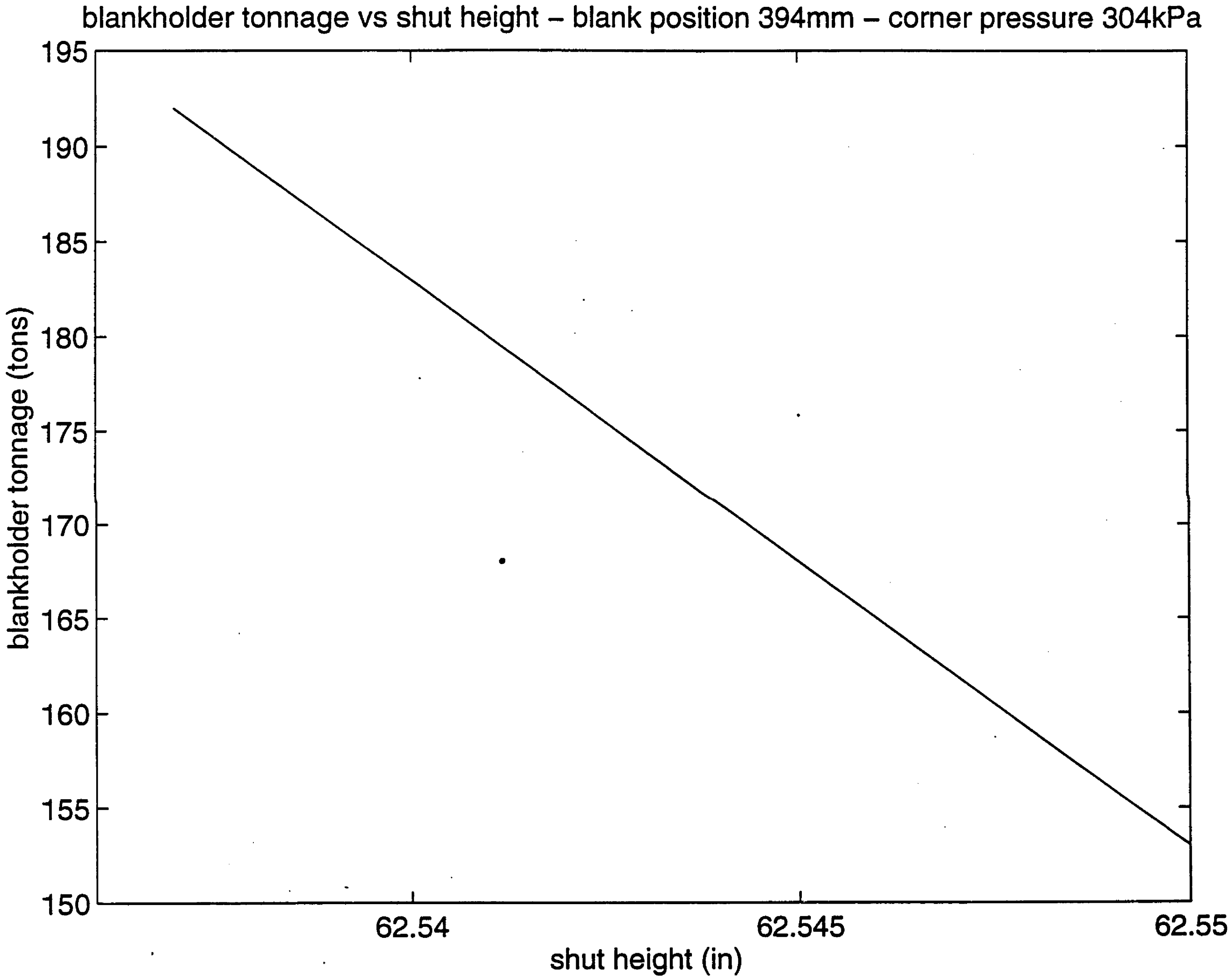

blankholder tonnage vs corner pressure - blank position 394mm - shut height 62.55in
blankholder tonnage (tons)
160
159
158
157
156
155
154
153
300
320
340
360
380
400
420
corner pressure (kPa)

Graph No.45



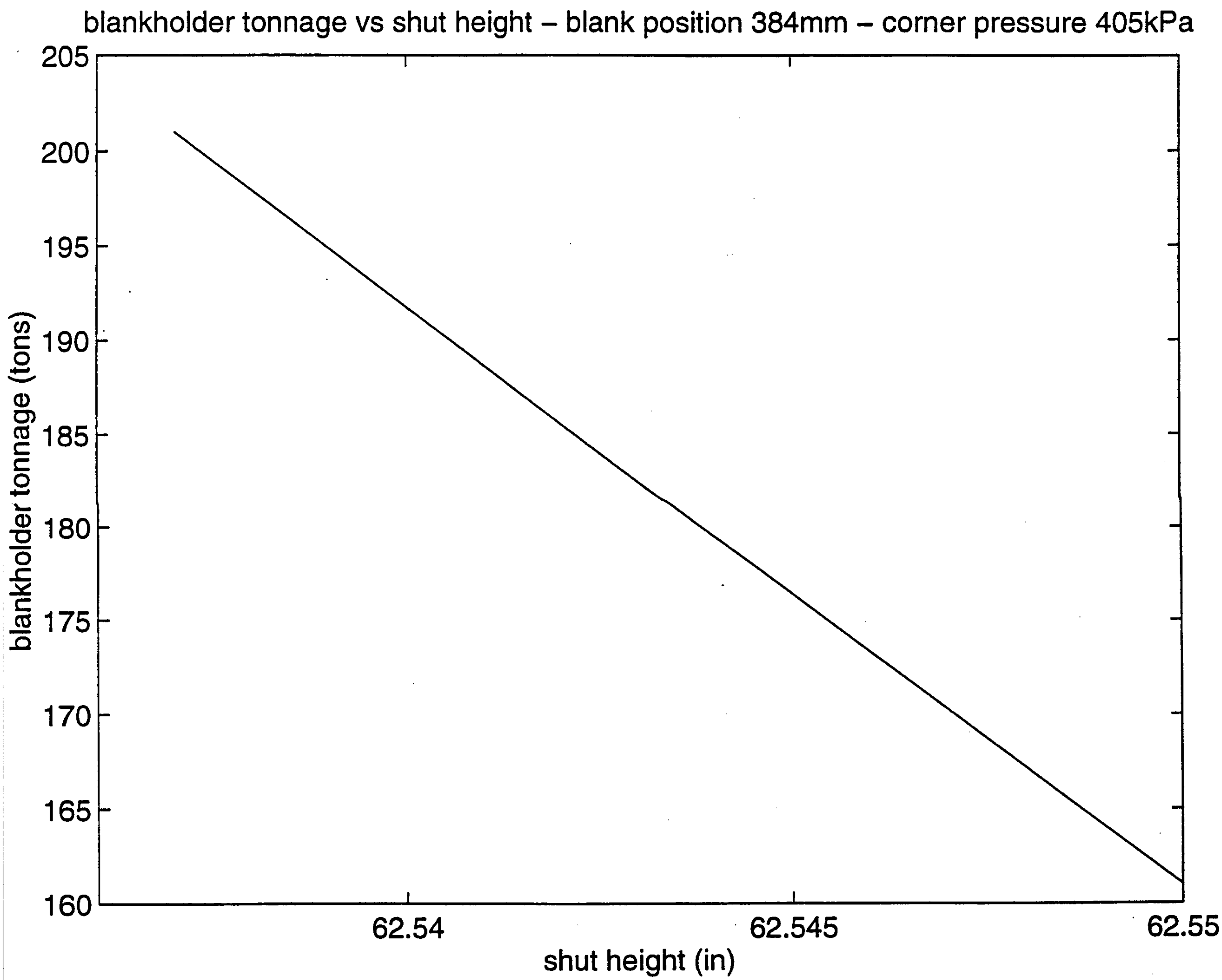
blankholder tonnage vs shut height – blank position 384mm – corner pressure 304kPa
200
190
180
170
160
150
140
130
blankholder tonnage (tons)
62.54
62.545
62.55
shut height (in)

Graph No.46



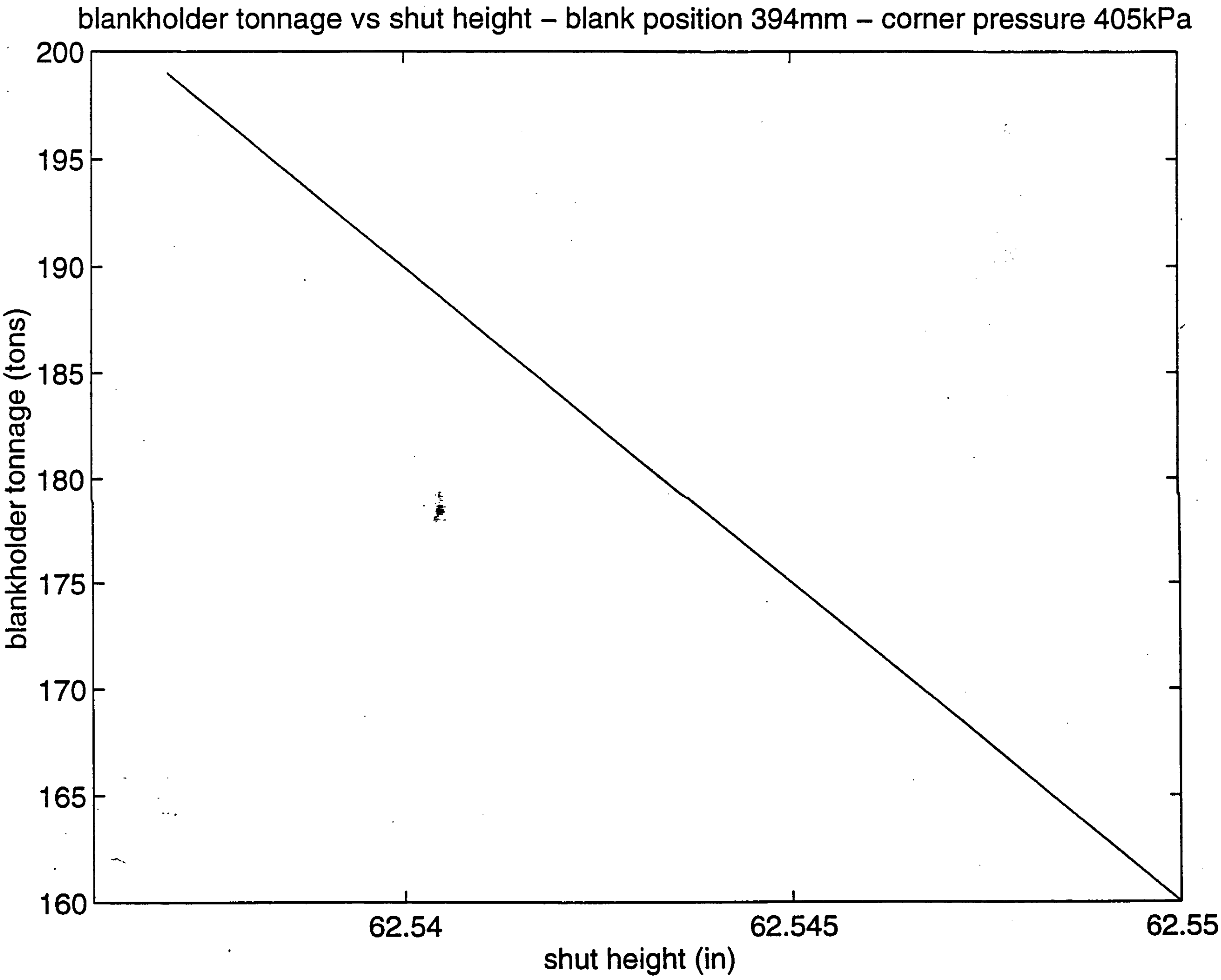
blankholder tonnage vs shut height - blank position 394mm - corner pressure 304kPa
195
190
185
180
175
170
165
160
155
150
blankholder tonnage (tons)
62.54
62.545
62.55
shut height (in)

Graph No.47



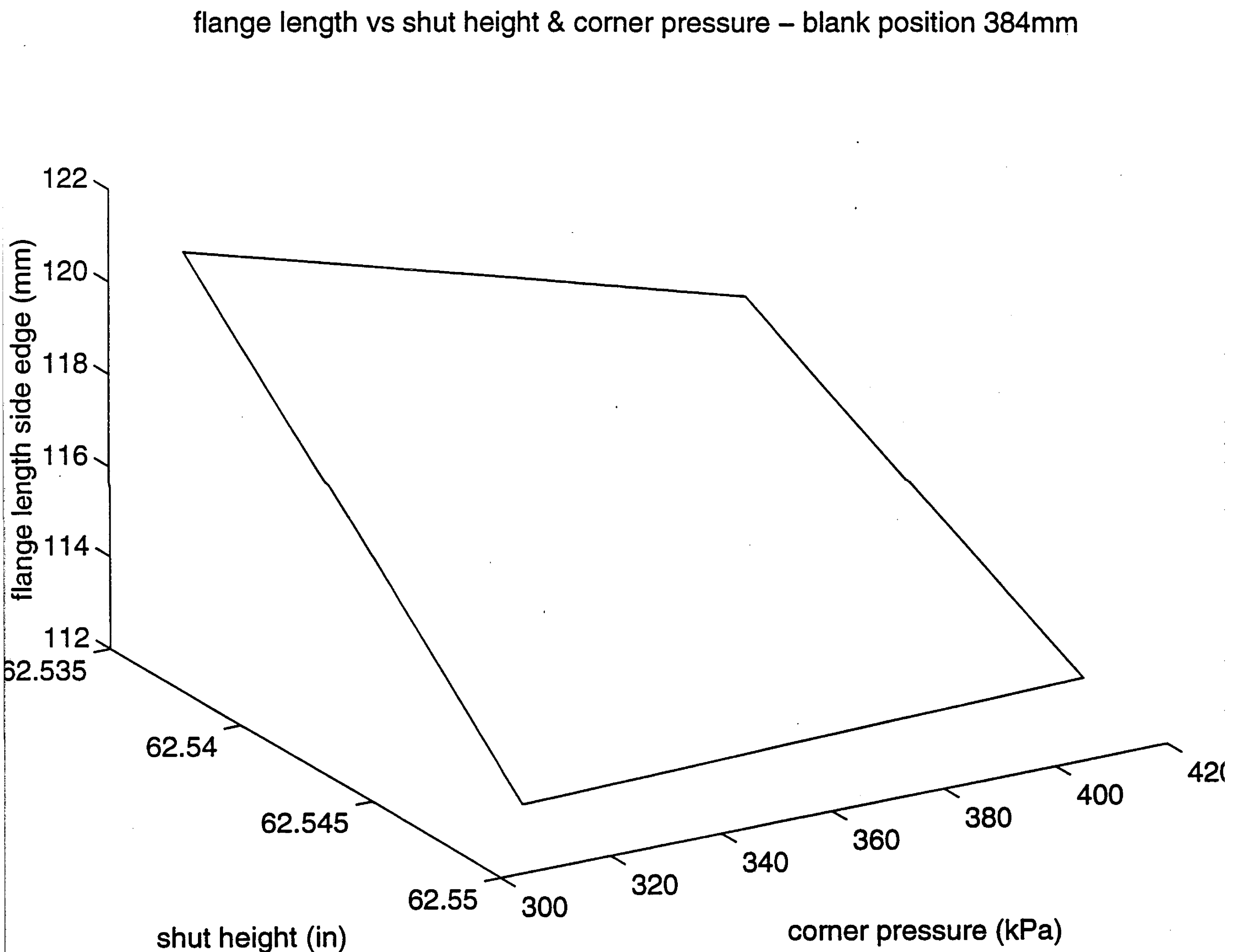
blankholder tonnage vs shut height - blank position 384mm - corner pressure 405kPa
205
200
195
190
185
180
175
170
165
160
blankholder tonnage (tons)
62.54
62.545
62.55
shut height (in)

Graph No.48



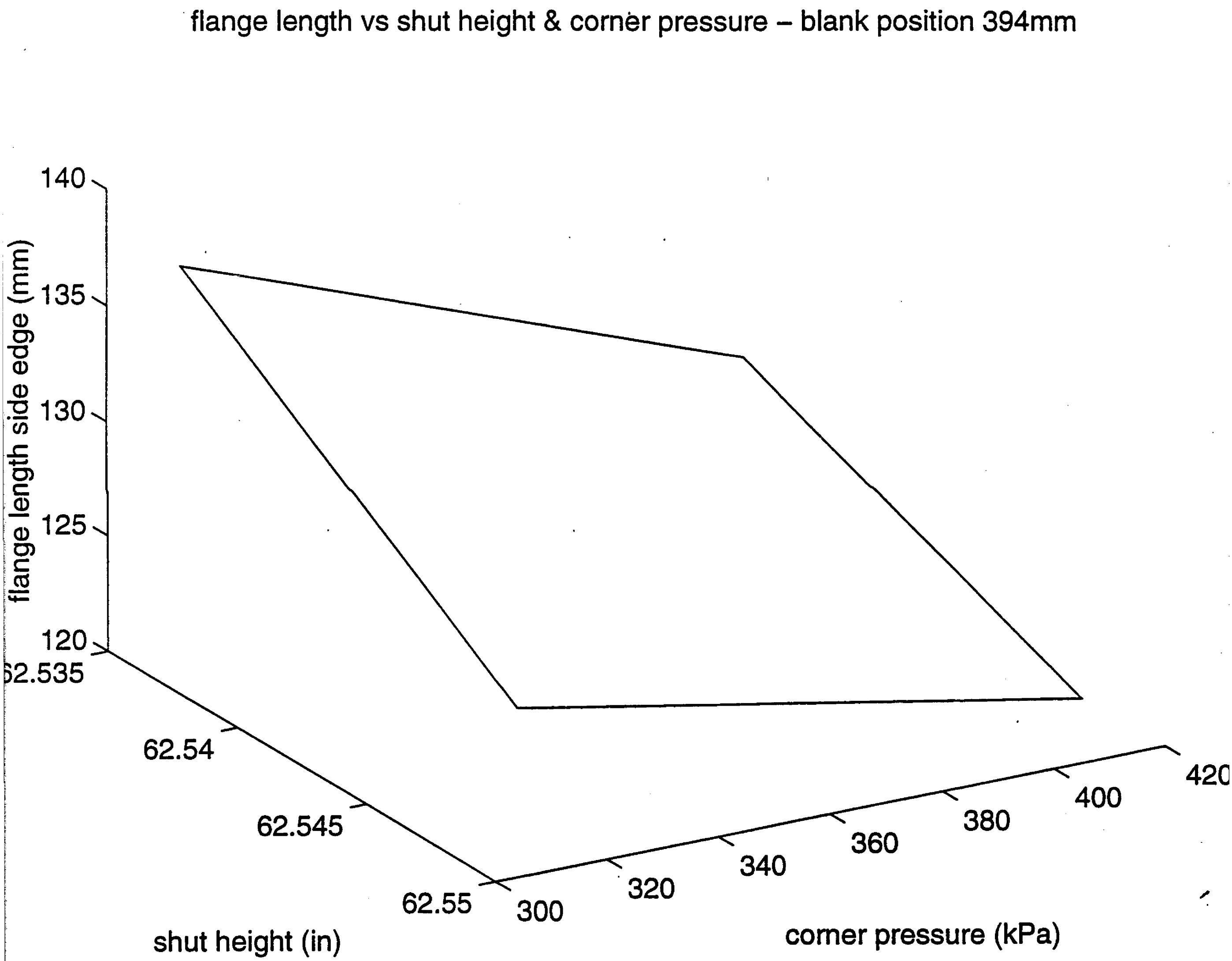
blankholder tonnage vs shut height – blank position 394mm – corner pressure 405kPa
200
195
190
185
180
175
170
165
160
blankholder tonnage (tons)
62.54
62.545
62.55
shut height (in)

Graph No.49



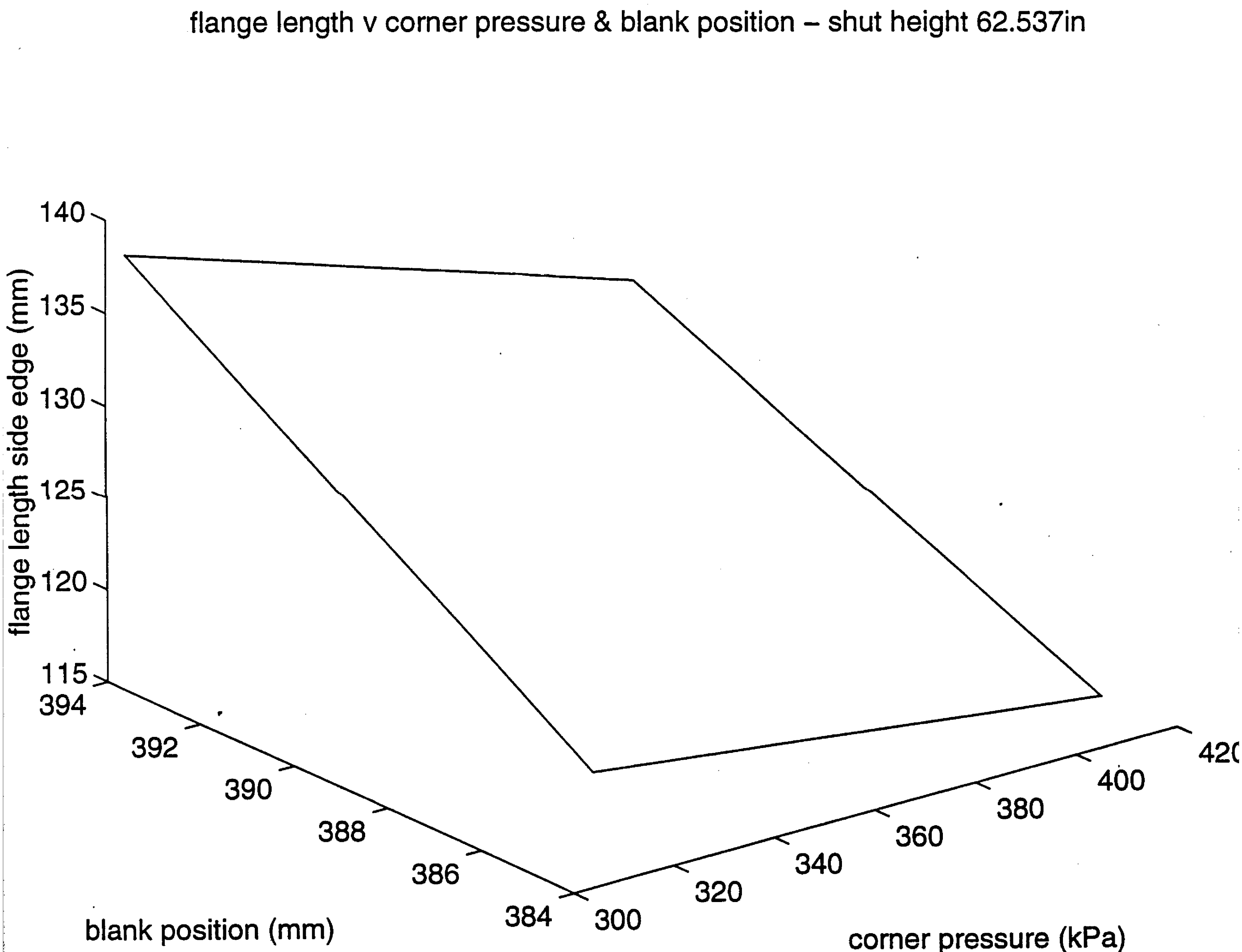
flange length vs shut height & corner pressure – blank position 384mm
flange length side edge (mm)
122
120
118
116
114
112
62.535
62.54
62.545
62.55
shut height (in)
300
320
340
360
380
400
corner pressure (kPa)

Graph No.50



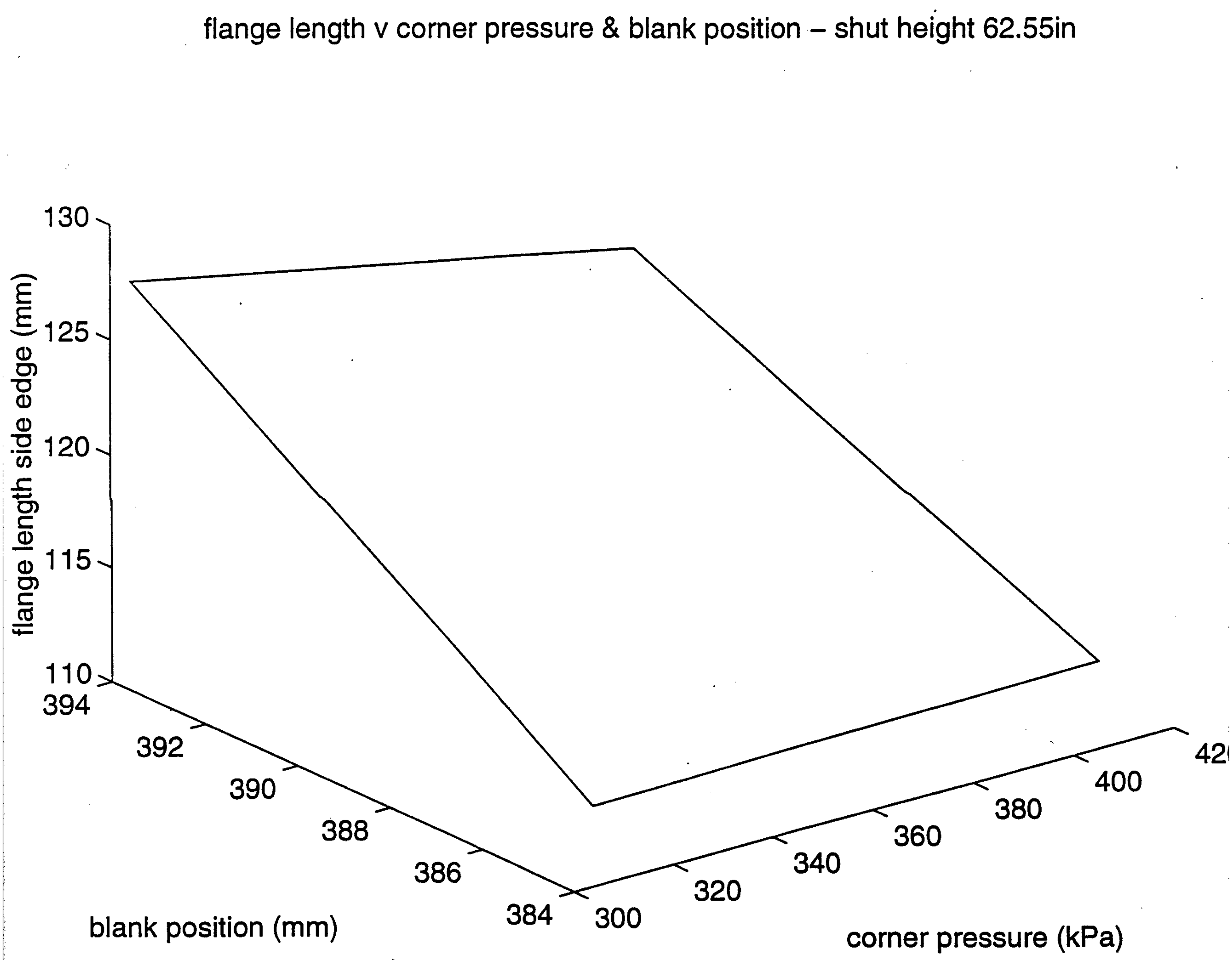
flange length vs shut height & corner pressure – blank position 394mm
140
135
130
125
120
flange length side edge (mm)
62.535
62.54
62.545
62.55
shut height (in)
300
320
340
360
380
400
420
corner pressure (kPa)

Graph No.51

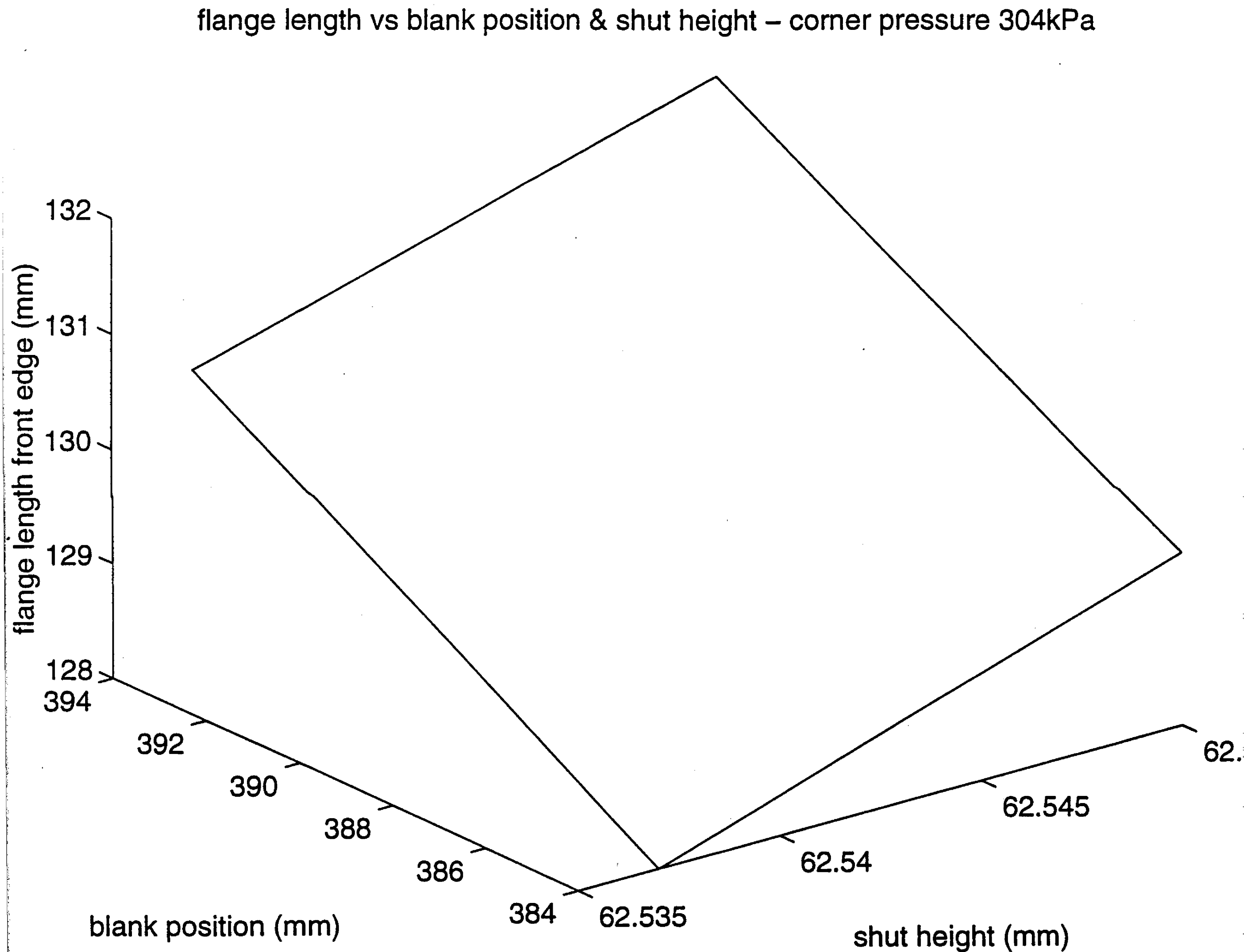


flange length v corner pressure & blank position – shut height 62.537in
flange length side edge (mm)
140
135
130
125
120
115
394
392
390
388
386
384
blank position (mm)
300
320
340
360
380
400
420
corner pressure (kPa)

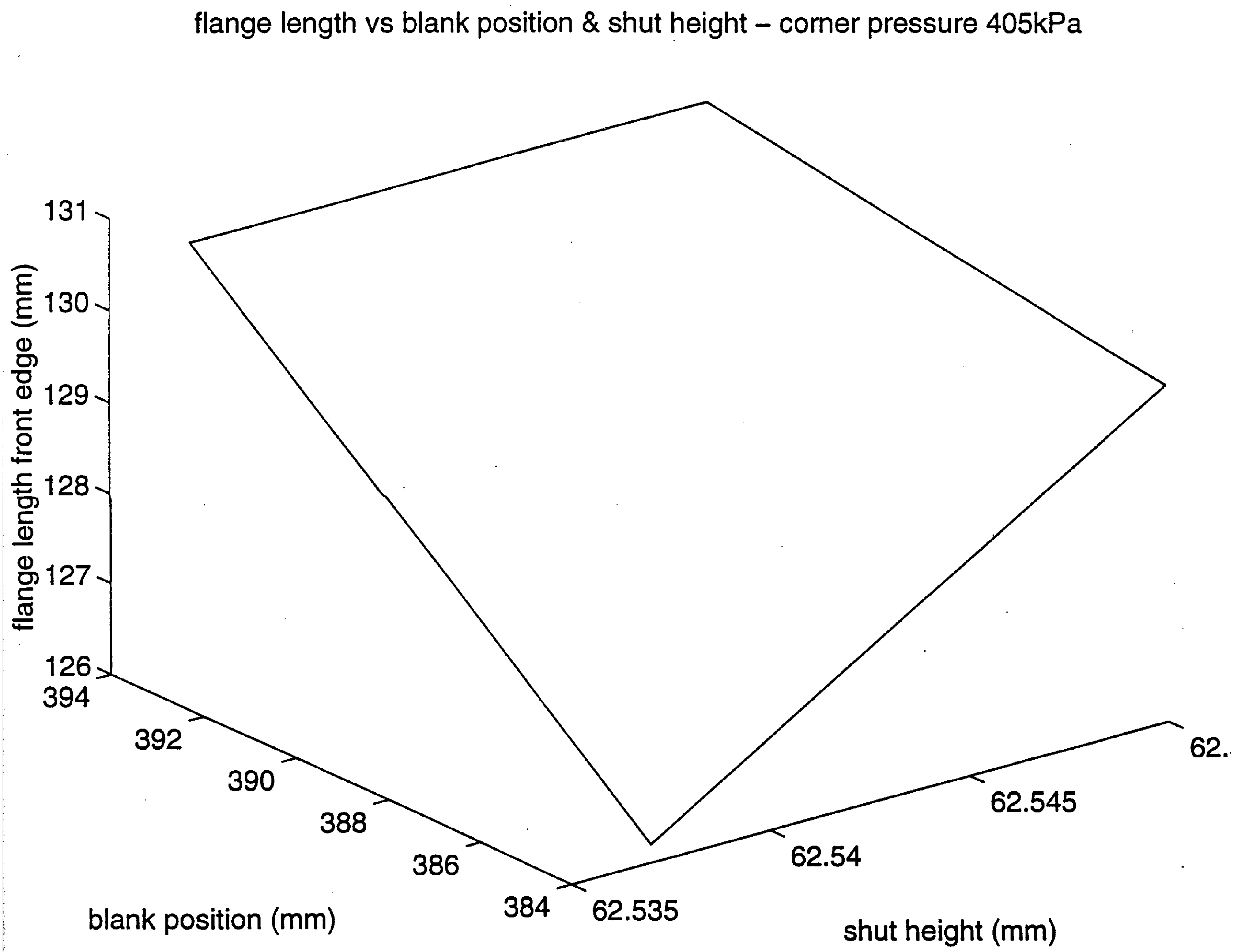
Graph No.52


flange length v corner pressure & blank position – shut height 62.55in
flange length side edge (mm)
130
125
120
115
110
394
392
390
388
386
384
blank position (mm)
300
320
340
360
380
400
42
corner pressure (kPa)

Graph No.53

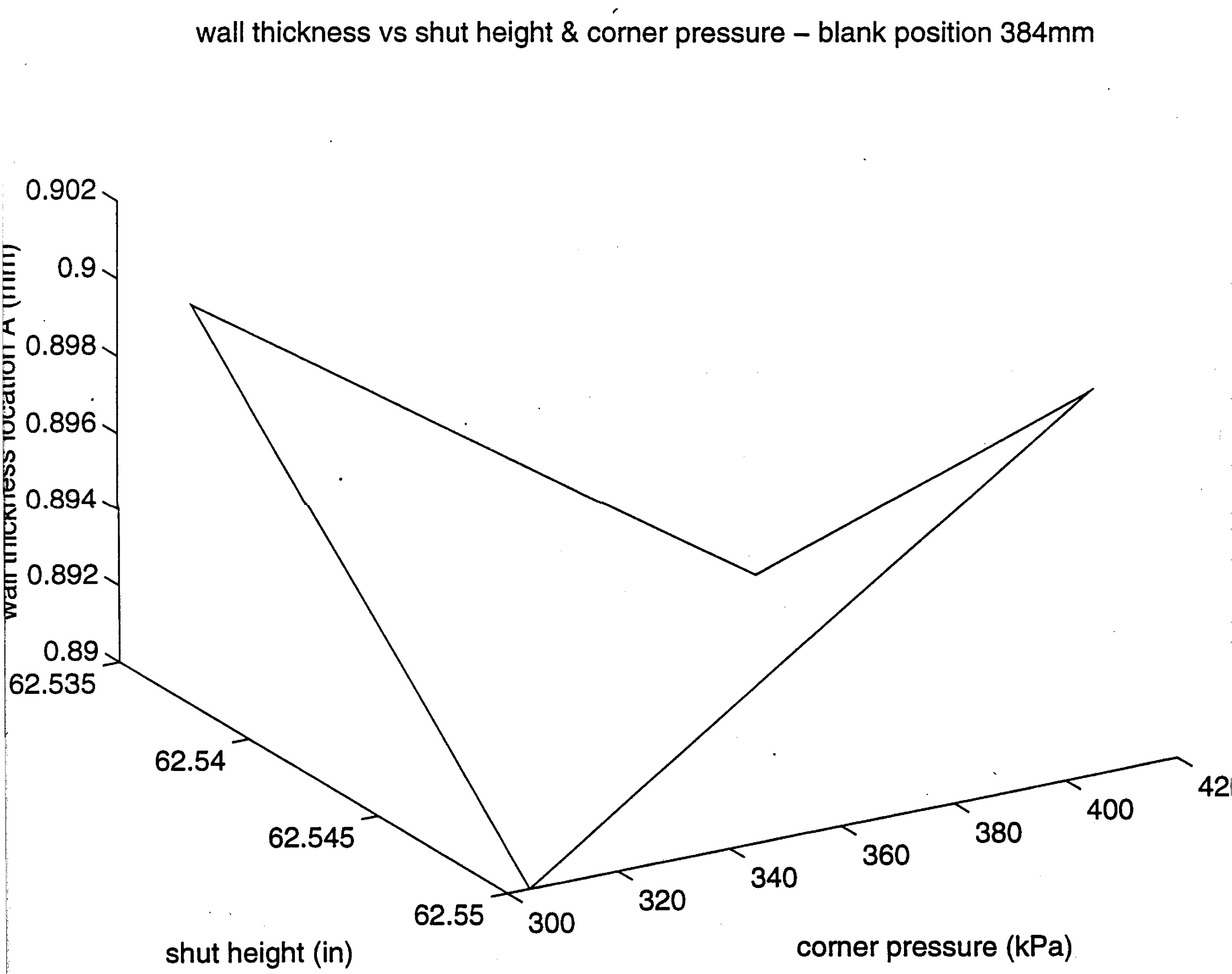

flange length vs blank position & shut height – corner pressure 304kPa
flange length front edge (mm)
132
131
130
129
128
394
392
390
388
386
384
blank position (mm)
62.535
62.54
62.545
62.
shut height (mm)

Graph No.54

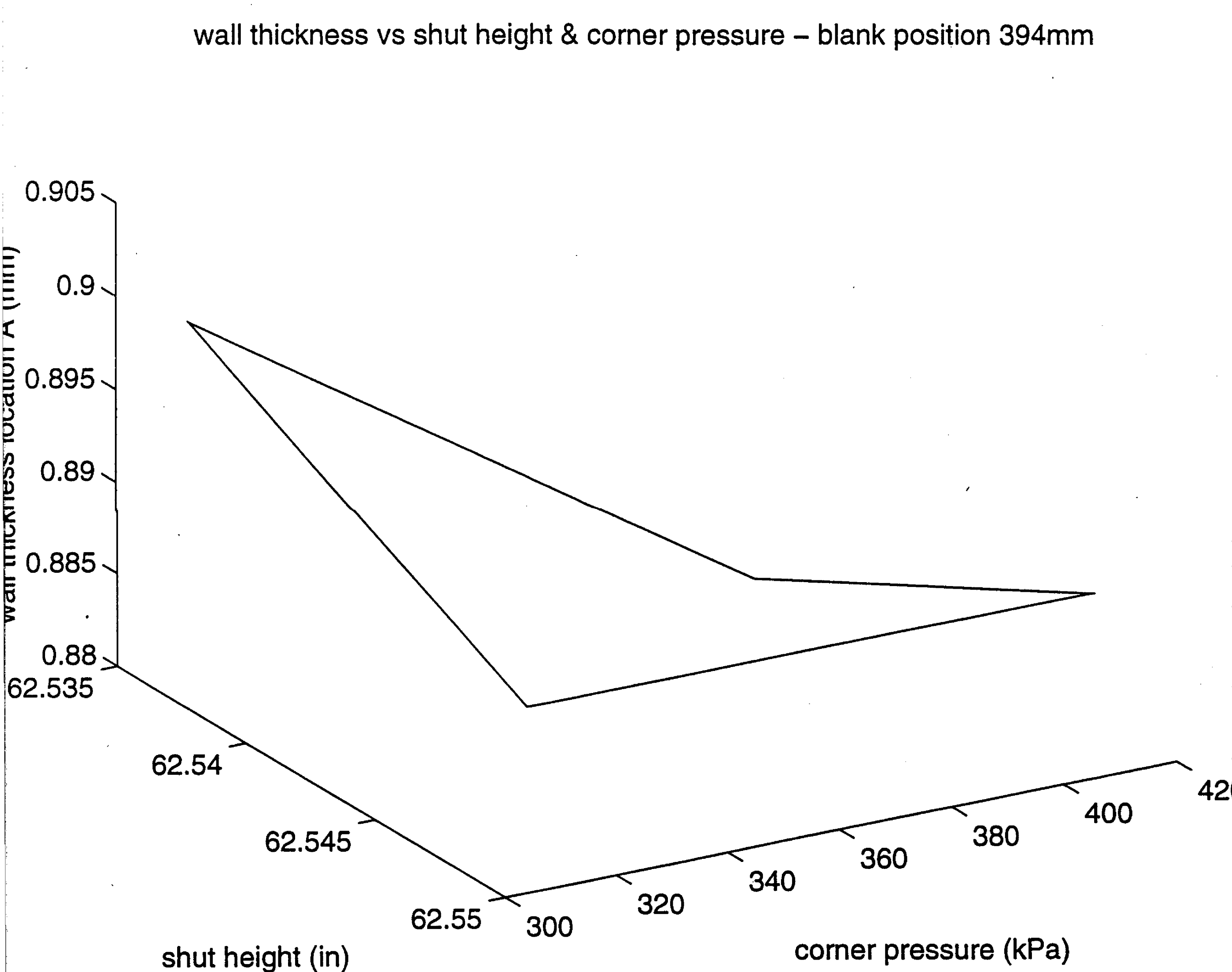


flange length vs blank position & shut height – corner pressure 405kPa
flange length front edge (mm)
131
130
129
128
127
126
394
392
390
388
386
384
blank position (mm)
62.535
62.54
62.545
62.
shut height (mm)

Graph No.55

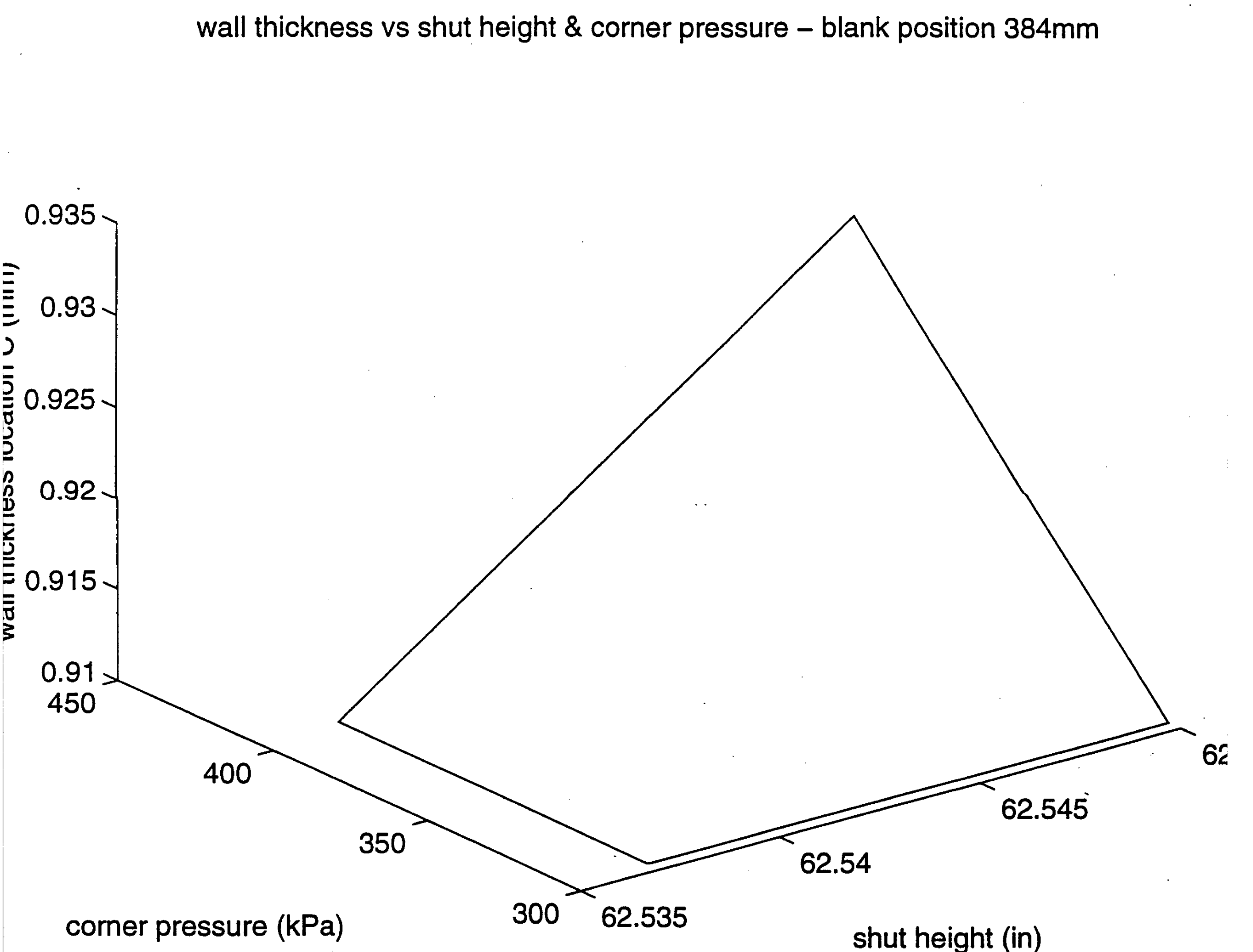

wall thickness vs shut height & corner pressure – blank position 384mm
wall thickness location A (mm)
0.902
0.9
0.898
0.896
0.894
0.892
0.89
62.535
62.54
62.545
62.55
shut height (in)
300
320
340
360
380
400
corner pressure (kPa)

Graph No.56



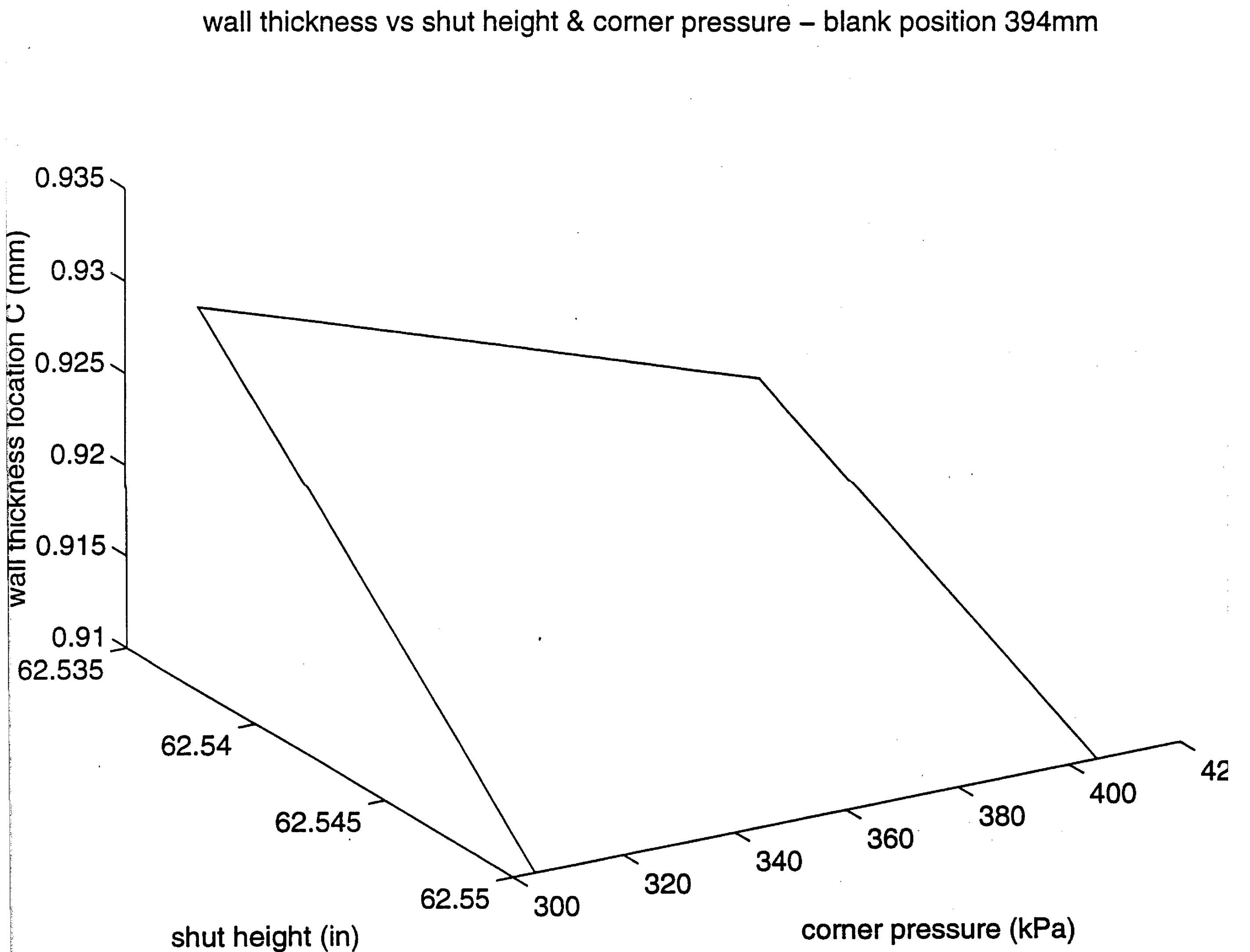
wall thickness vs shut height & corner pressure – blank position 394mm
0.905
0.9
0.895
0.89
0.885
0.88
62.535
62.54
62.545
62.55
shut height (in)
300
320
340
360
380
400
corner pressure (kPa)

Graph No.57



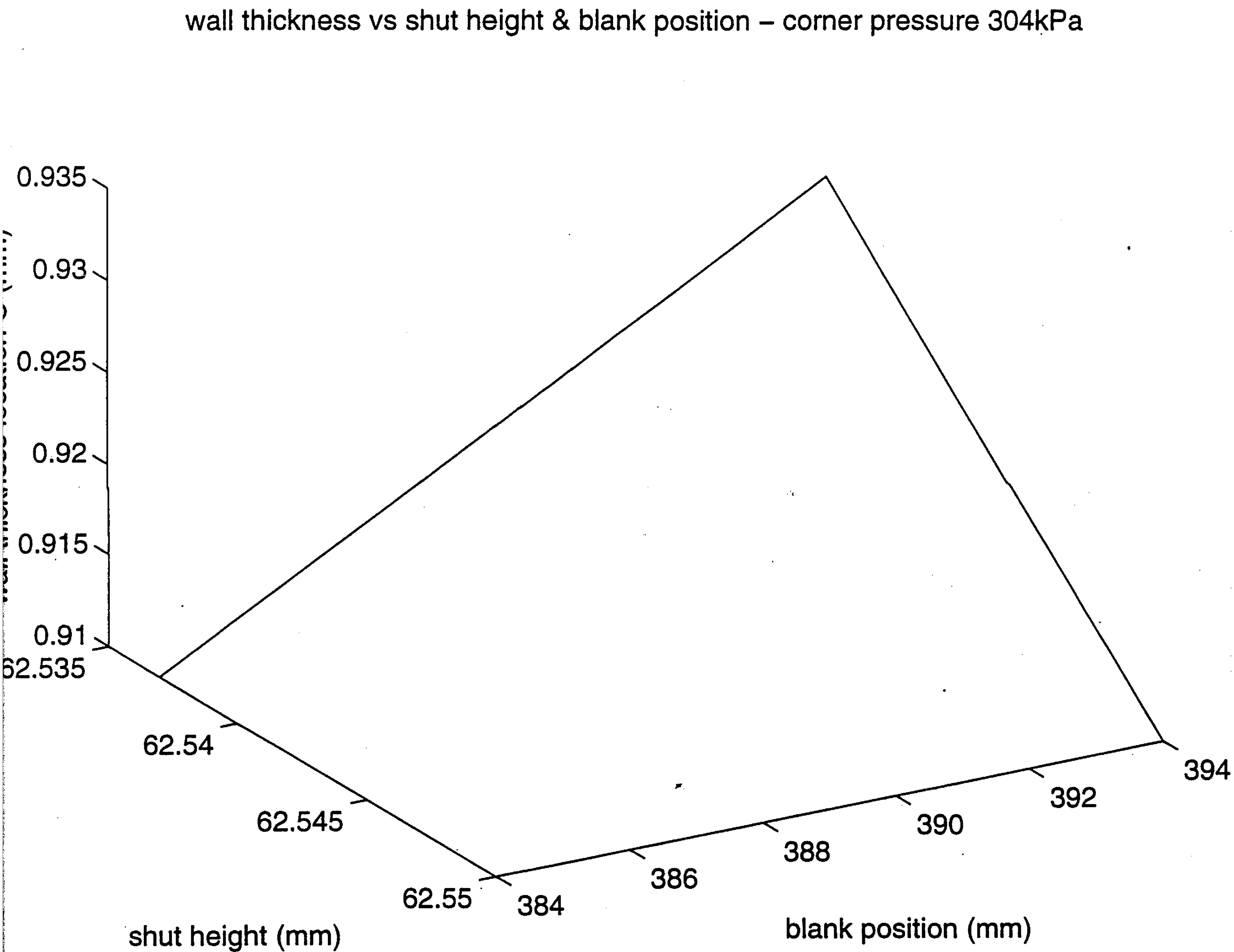
wall thickness vs shut height & corner pressure – blank position 384mm
0.935
0.93
0.925
0.92
0.915
0.91
450
400
350
300
corner pressure (kPa)
62.535
62.54
62.545
shut height (in)

Graph No.58



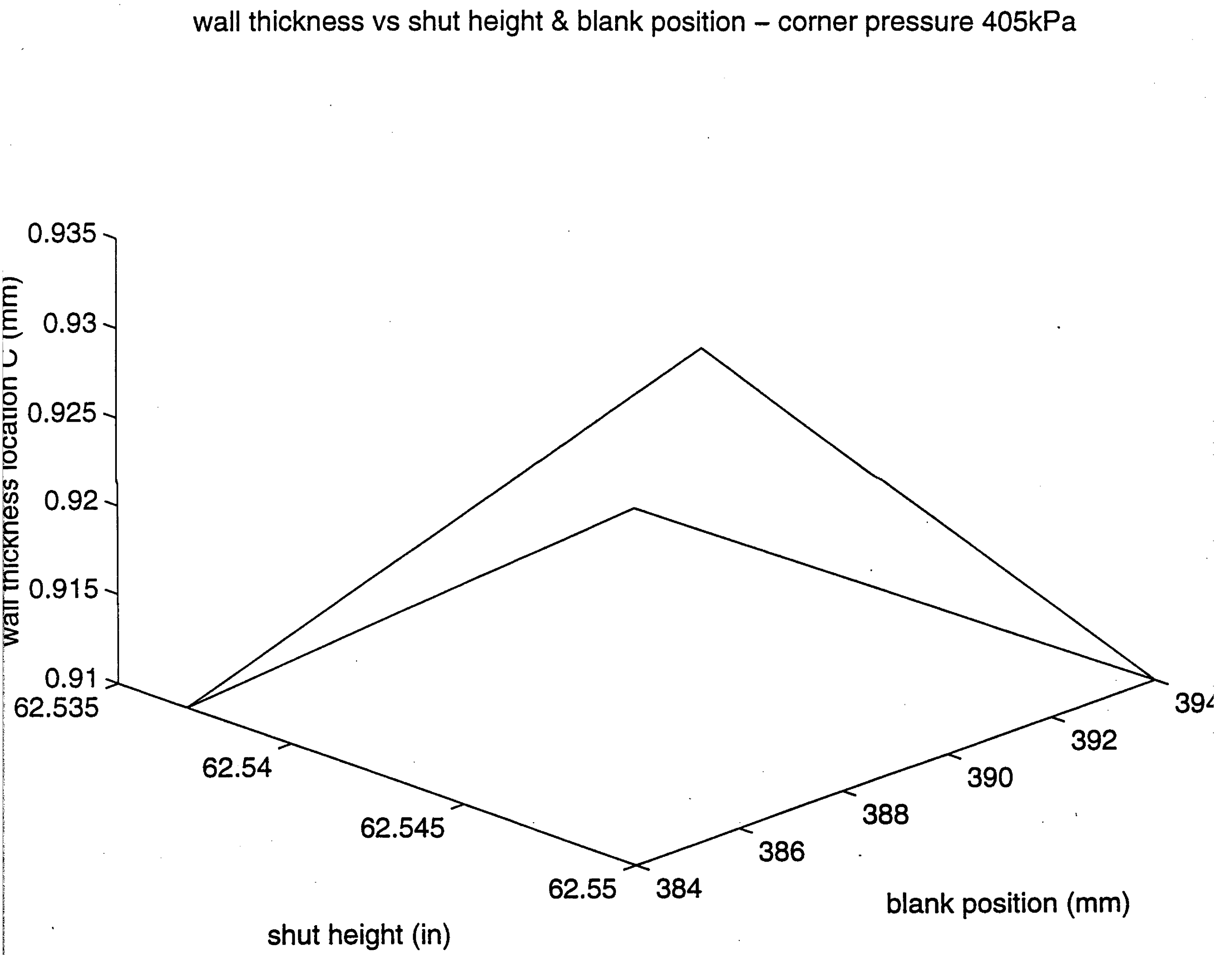
wall thickness vs shut height & corner pressure – blank position 394mm
0.935
0.93
0.925
0.92
0.915
0.91
wall thickness location C (mm)
62.535
62.54
62.545
62.55
shut height (in)
300
320
340
360
380
400
42
corner pressure (kPa)

Graph No.59



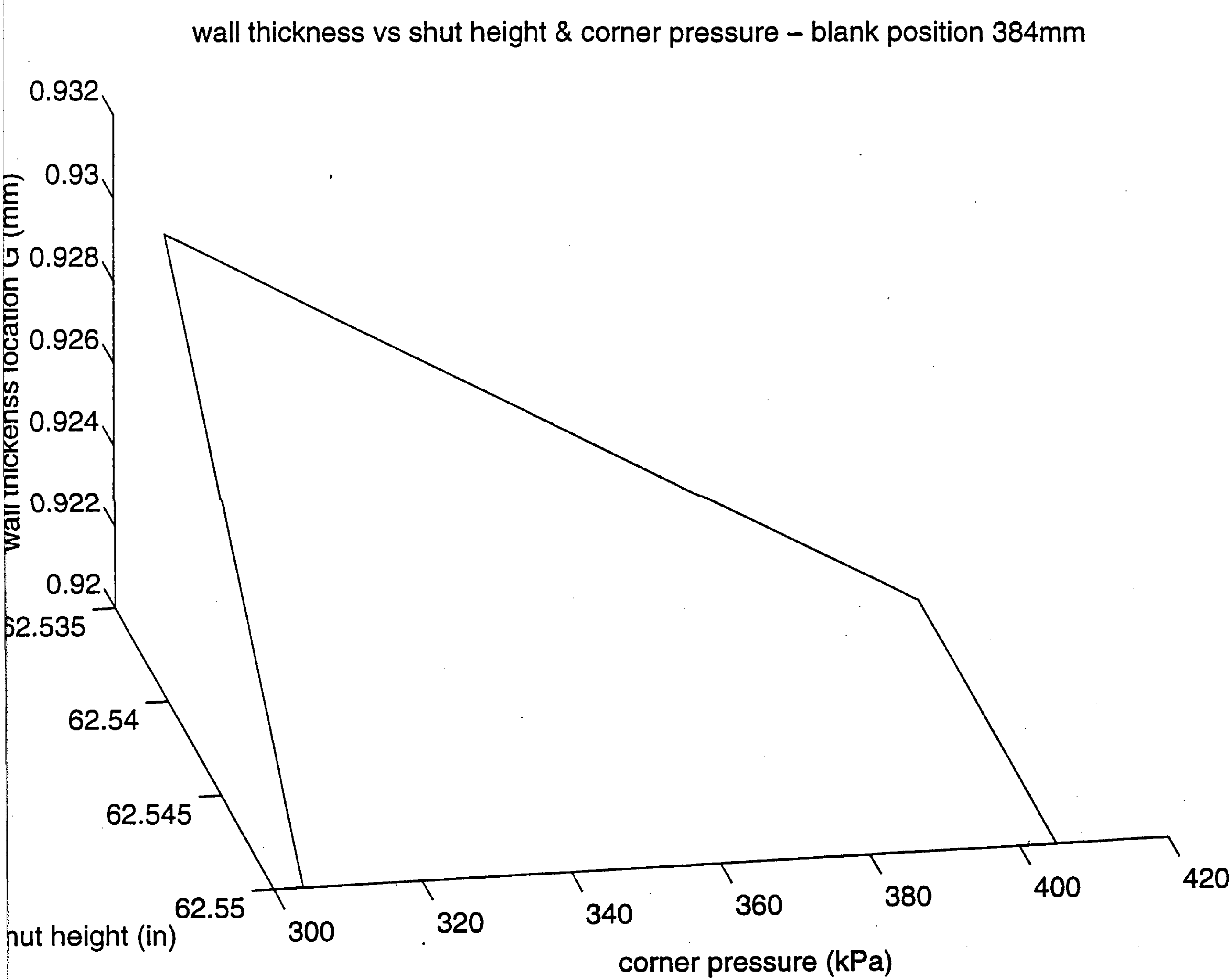
wall thickness vs shut height & blank position – corner pressure 304kPa
0.935
0.93
0.925
0.92
0.915
0.91
62.535
62.54
62.545
62.55
shut height (mm)
384
386
388
390
392
394
blank position (mm)

Graph No.60



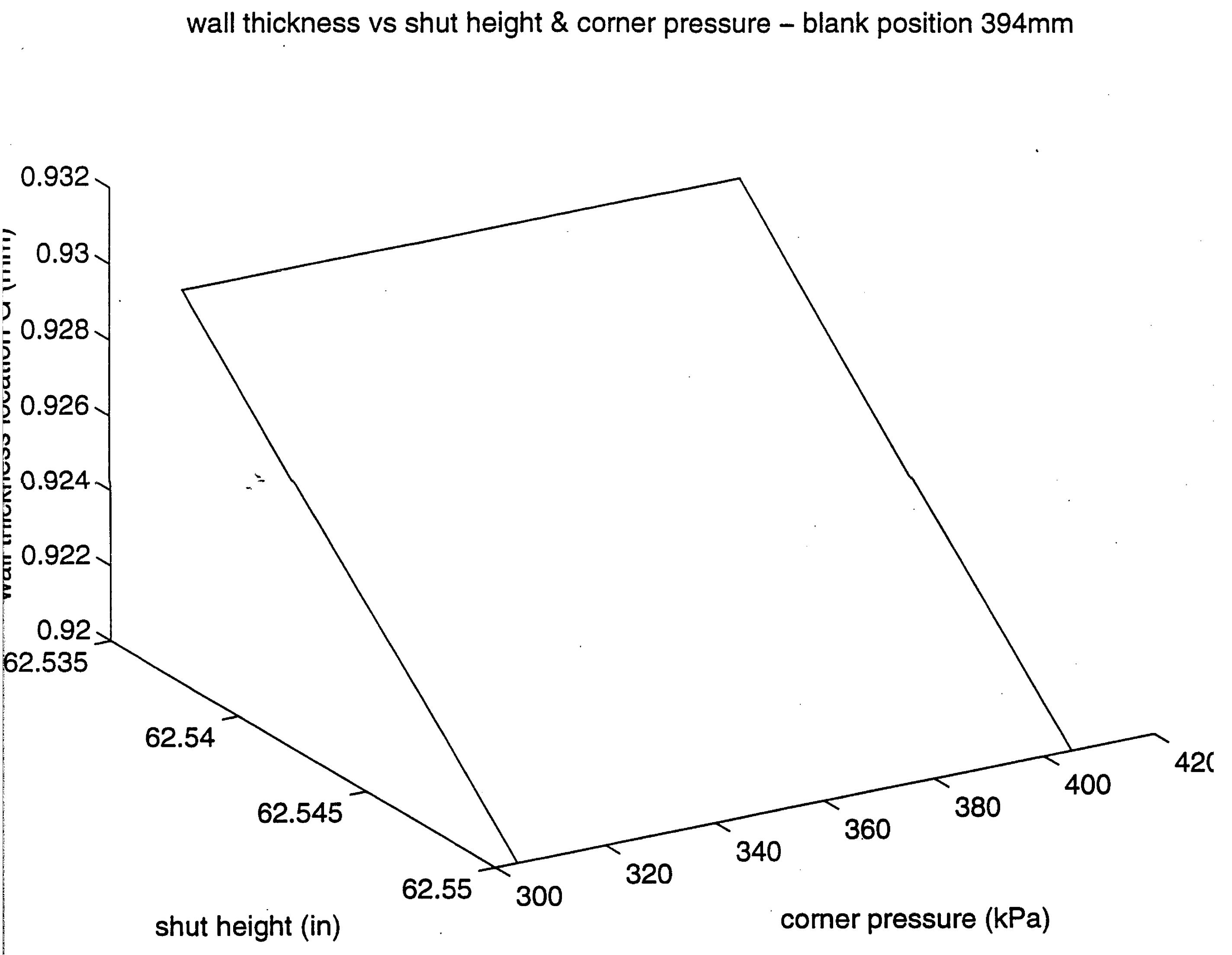
wall thickness vs shut height & blank position – corner pressure 405kPa
0.935
0.93
0.925
0.92
0.915
0.91
wall thickness location C (mm)
62.535
62.54
62.545
62.55
shut height (in)
384
386
388
390
392
394
blank position (mm)

Graph No.61



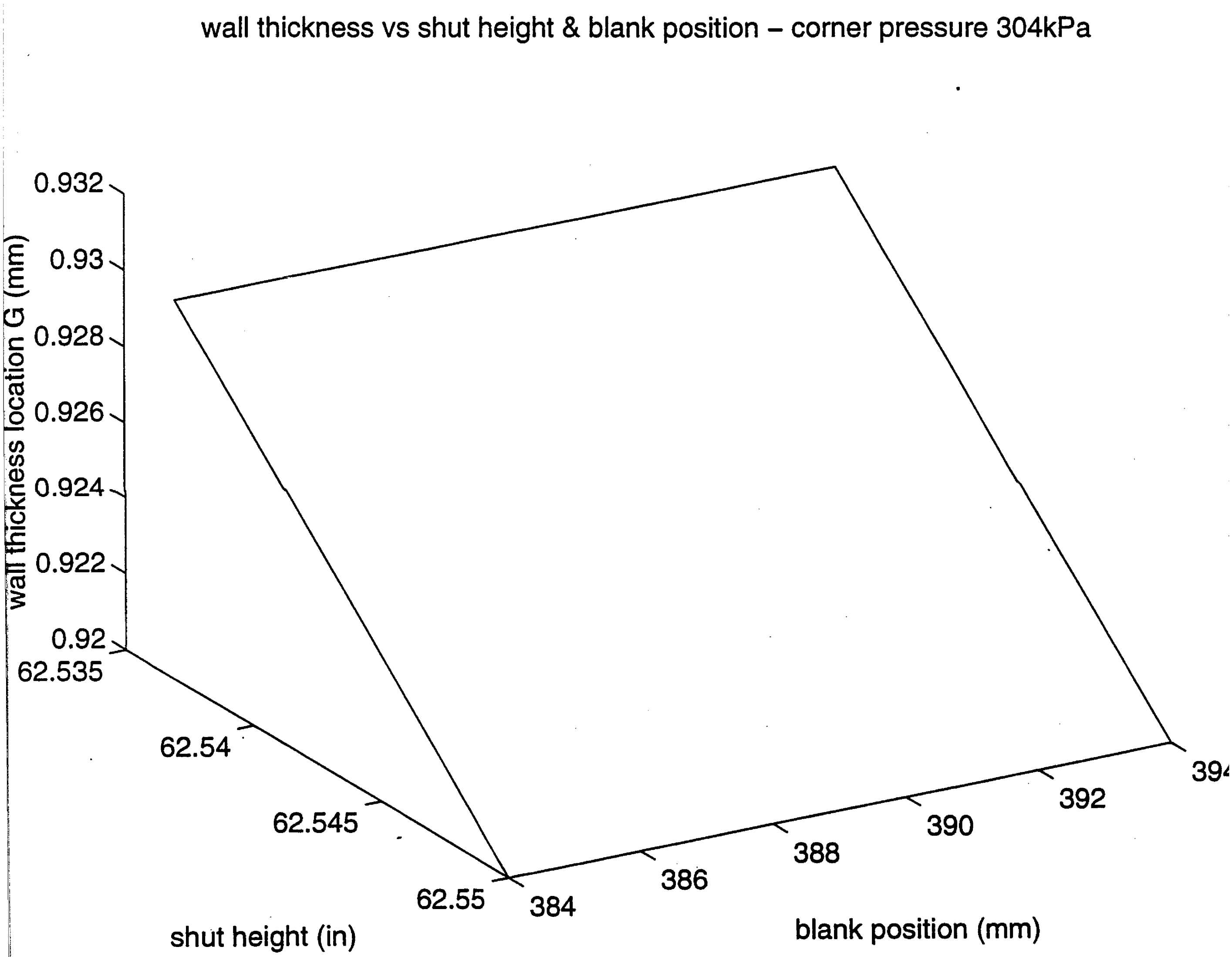
wall thickness vs shut height & corner pressure – blank position 384mm
0.932
0.93
0.928
0.926
0.924
0.922
0.92
wall thickenss location G (mm)
62.535
62.54
62.545
62.55
shut height (in)
300
320
340
360
380
400
420
corner pressure (kPa)

Graph No.62

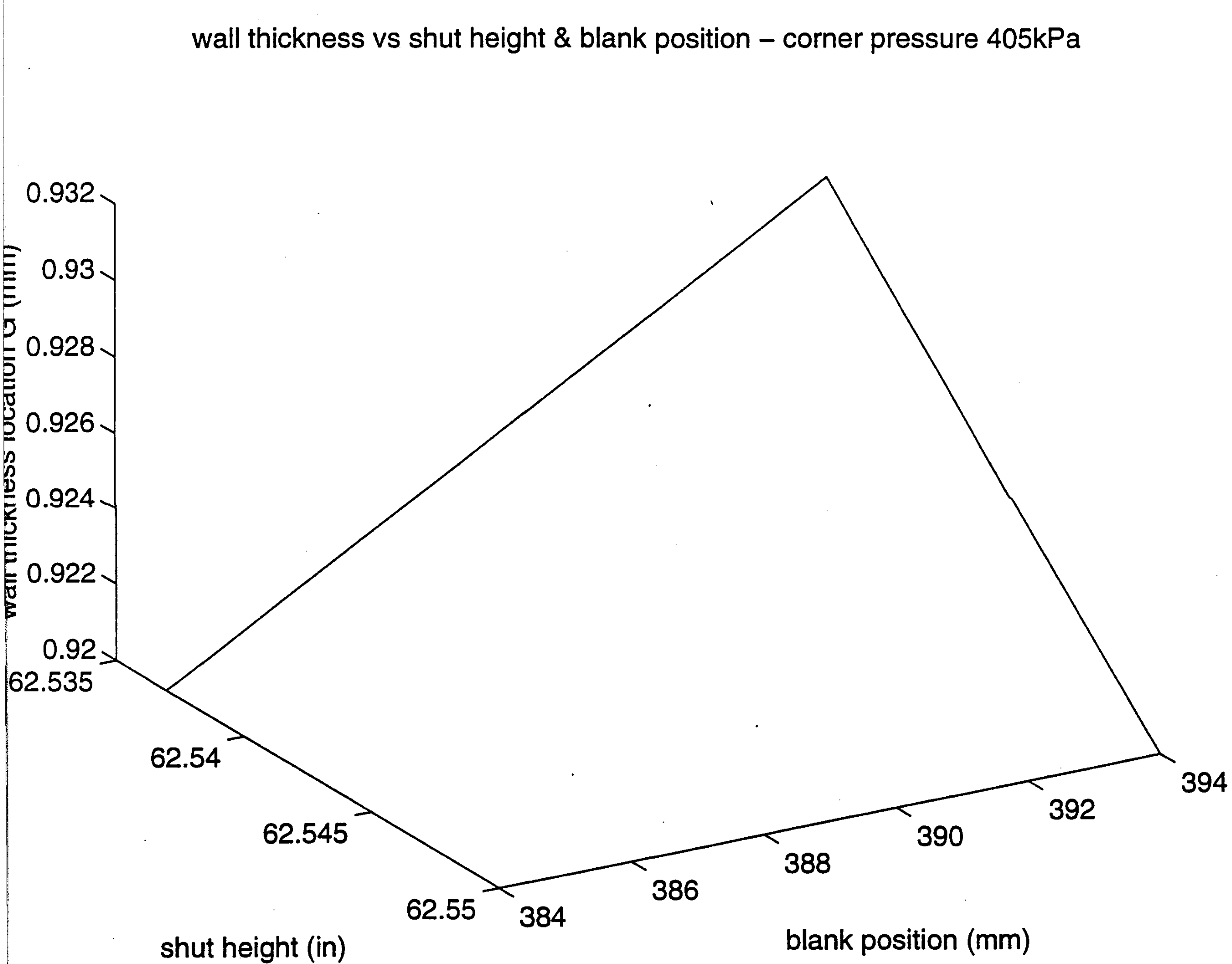


wall thickness vs shut height & corner pressure – blank position 394mm
0.932
0.93
0.928
0.926
0.924
0.922
0.92
62.535
62.54
62.545
62.55
shut height (in)
300
320
340
360
380
400
corner pressure (kPa)

Graph No.63

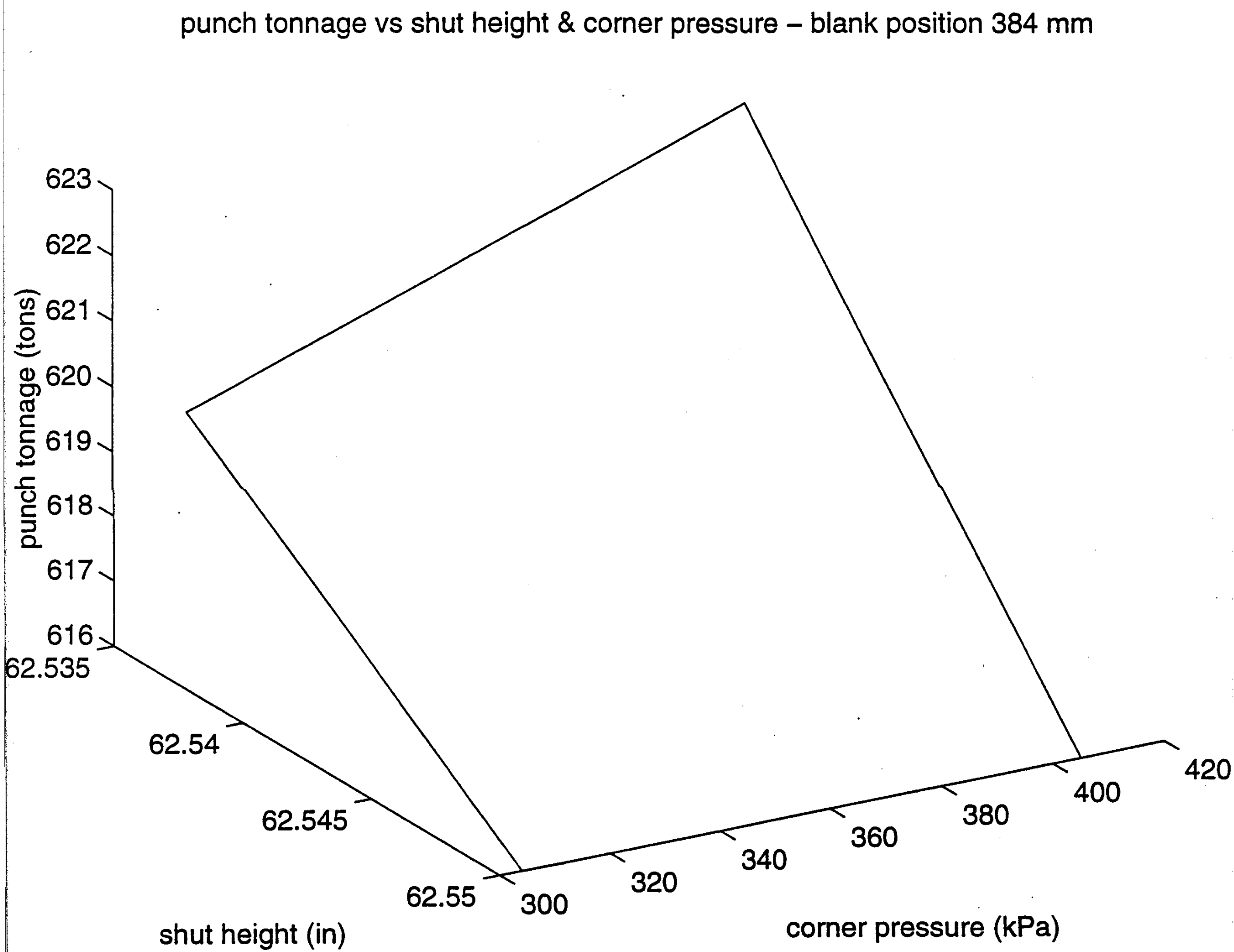

wall thickness vs shut height & blank position – corner pressure 304kPa
wall thickness location G (mm)
0.932
0.93
0.928
0.926
0.924
0.922
0.92
62.535
62.54
62.545
62.55
shut height (in)
384
386
388
390
392
394
blank position (mm)

Graph No.64



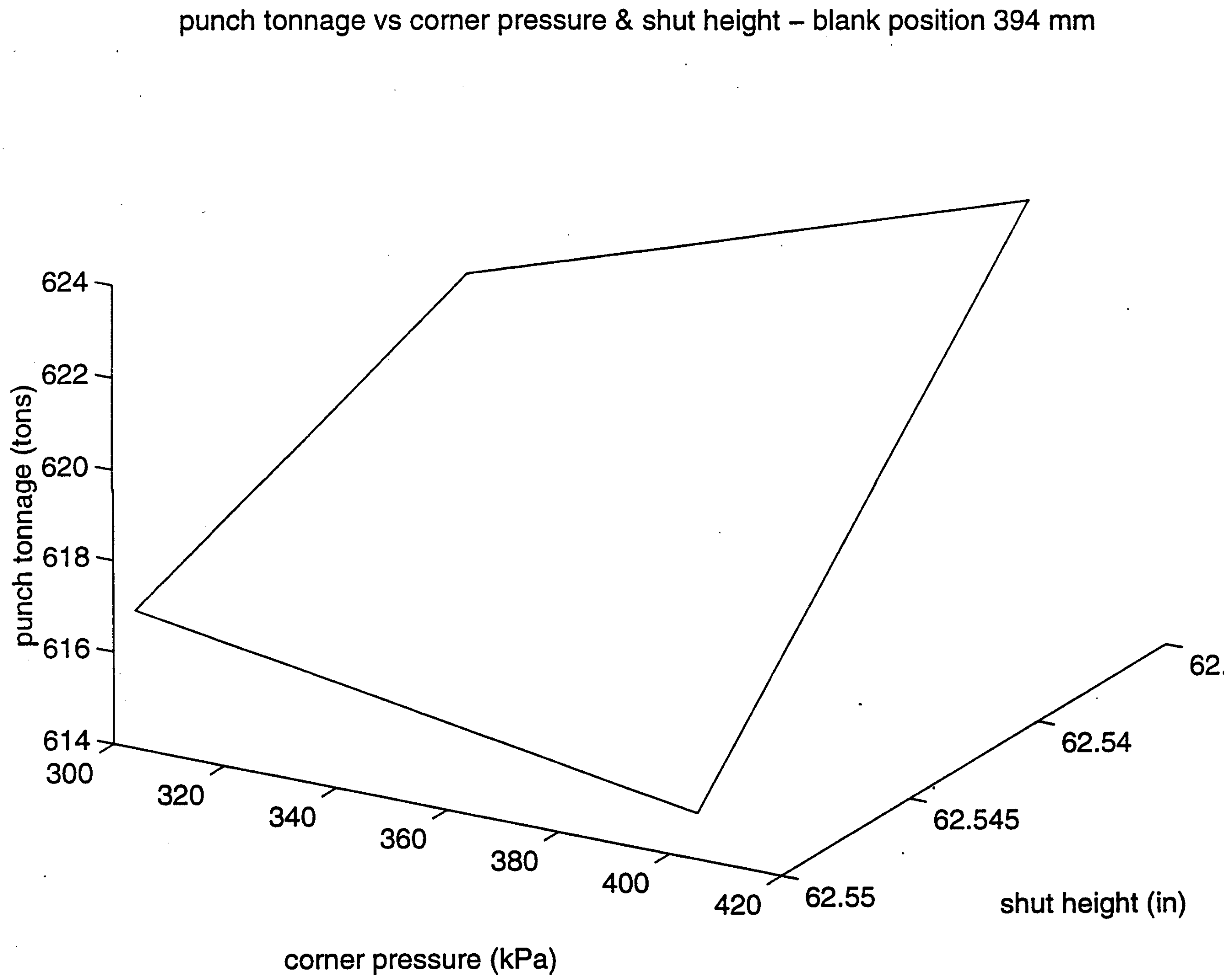
wall thickness vs shut height & blank position – corner pressure 405kPa
0.932
0.93
0.928
0.926
0.924
0.922
0.92
62.535
62.54
62.545
62.55
384
386
388
390
392
394
shut height (in)
blank position (mm)

Graph No.65

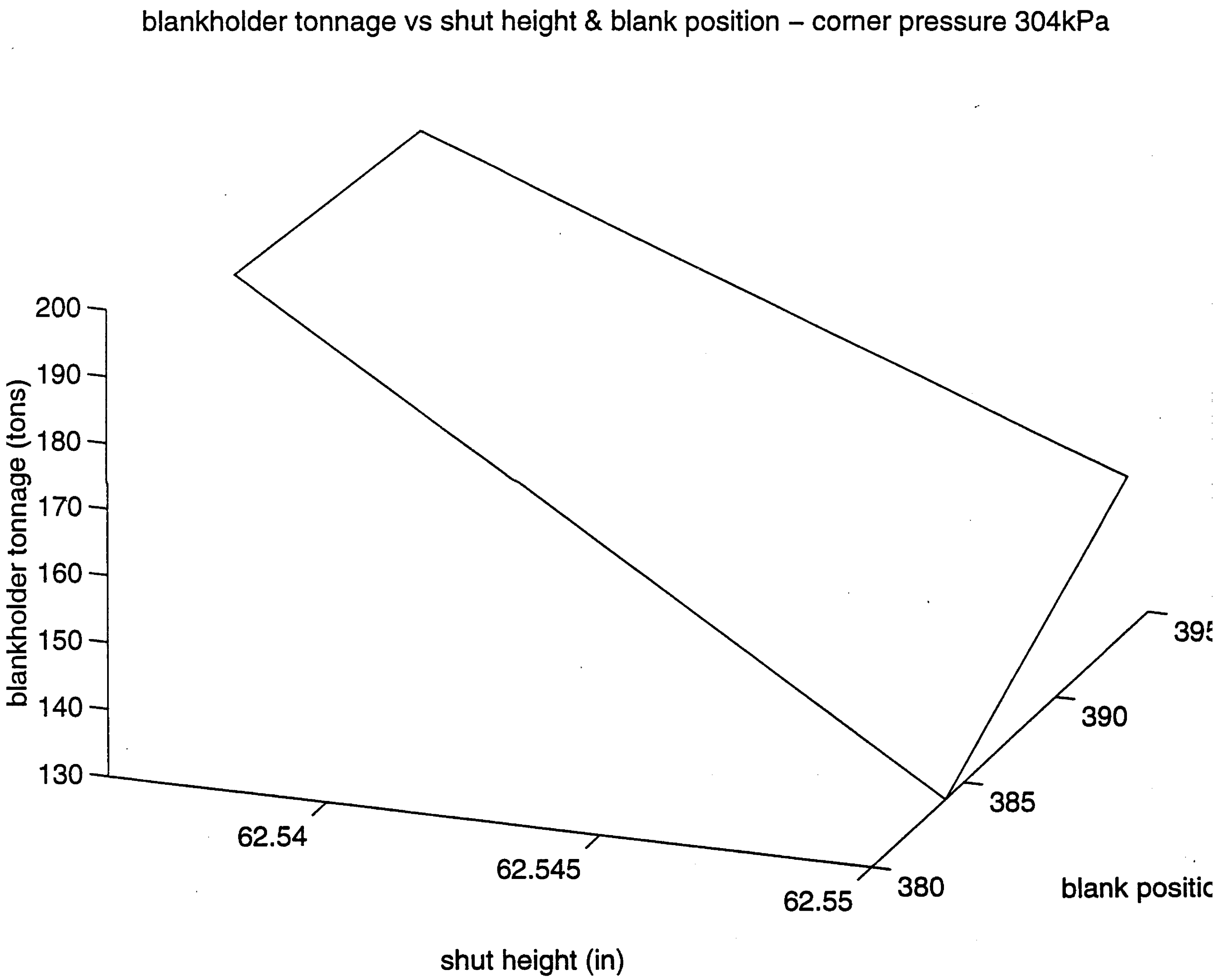


punch tonnage vs shut height & corner pressure – blank position 384 mm
punch tonnage (tons)
623
622
621
620
619
618
617
616
62.535
62.54
62.545
62.55
shut height (in)
300
320
340
360
380
400
420
corner pressure (kPa)

Graph No.66

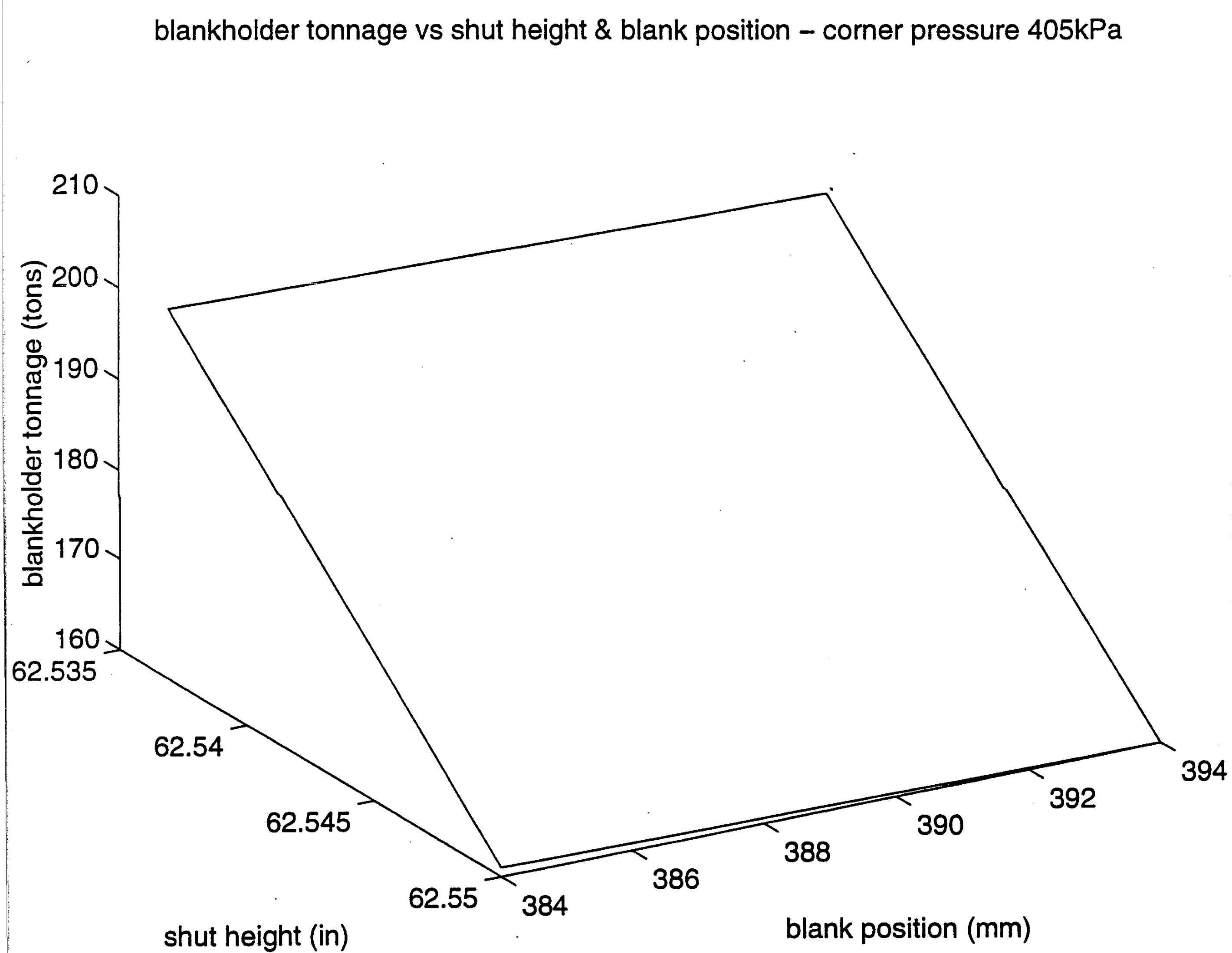

punch tonnage vs corner pressure & shut height – blank position 394 mm
punch tonnage (tons)
624
622
620
618
616
614
300
320
340
360
380
400
420
corner pressure (kPa)
62.55
62.545
62.54
62.
shut height (in)

Graph No.67



blankholder tonnage vs shut height & blank position – corner pressure 304kPa
blankholder tonnage (tons)
200
190
180
170
160
150
140
130
62.54
62.545
62.55
shut height (in)
380
385
390
395
blank positic

Graph No.68


blankholder tonnage vs shut height & blank position – corner pressure 405kPa
blankholder tonnage (tons)
210
200
190
180
170
160
62.535
62.54
62.545
62.55
shut height (in)
384
386
388
390
392
394
blank position (mm)

APPENDIX4

Experiment No.1					
Inputs			Setting		
a) Shut Height			62.527	in	
b) Blank Position			374	mm	
Outputs		Specimen No.1	Specimen No.2	Specimen No.3	
a) Flange Length Front Edge		131	129	127.5	mm
b) Flange Length Side Edge		125	131	130	mm
c) Flange Length Left Edge		107	95	95	mm
d) Flange Length Rear Edge		59.5	62.5	65.5	mm
e) Peak Punch Tonnage		326	328	334	mm
f) Peak Blankholder Tonnage		205	204	208	tons
g) Corner Tonnages					
	LF	50	49	52	tons
	LR	44	44	45	tons
	RR	59	57	59	tons
	RF	55	56	56	tons

Table1

Experiment No.2					
Inputs			Setting		
a) Shut Height			62.56	in	
b) Blank Position			374	mm	
Outputs		Specimen No.1	Specimen No.2	Specimen No.3	
a) Flange Length Front Edge		134	133	134	mm
b) Flange Length Side Edge		114.5	113.5	112.5	mm
c) Flange Length Left Edge		84.5	83.5	85	mm
d) Flange Length Rear Edge		75	77.5	78	mm
e) Peak Punch Tonnage		334	333	331	mm
f) Peak Blankholder Tonnage		107	106	98	tons
g) Corner Tonnages					
	LF	24	24	22	tons
	LR	20	20	20	tons
	RR	33	34	32	tons
	RF	32	30	26	tons

Table2

Experiment No.3					
Inputs			Setting		
a) Shut Height			62.527	in	
b) Blank Position			404	mm	
Outputs		Specimen No.1	Specimen No.2	Specimen No.3	
a) Flange Length Front Edge		130	138	132.5	mm
b) Flange Length Side Edge		170	175	172	mm
c) Flange Length Left Edge		75	63	68	mm
d) Flange Length Rear Edge		57.5	54.5	58	mm
e) Peak Punch Tonnage		334	337	336	mm
f) Peak Blankholder Tonnage		202	200	198	tons
g) Corner Tonnages					
	LF	51	49	50	tons
	LR	43	43	44	tons
	RR	59	58	55	tons
	RF	56	53	53	tons

Table3

Experiment No.4					
Inputs			Setting		
a) Shut Height			62.56	in	
b) Blank Position			404	mm	
Outputs		Specimen No.1	Specimen No.2	Specimen No.3	
a) Flange Length Front Edge		136	136	137	mm
b) Flange Length Side Edge		160	158	162	mm
c) Flange Length Left Edge		50.5	48	45	mm
d) Flange Length Rear Edge		71.5	73	74.5	mm
e) Peak Punch Tonnage		330	339	333	mm
f) Peak Blankholder Tonnage		110	103	107	tons
g) Corner Tonnages					
	LF	23	26	23	tons
	LR	22	20	22	tons
	RR	34	34	33	tons
	RF	31	28	30	tons

Table4

Experiment No.5					
Inputs			Setting		
a) Shut Height			62.57	in	
b) Blank Position			374	mm	
Outputs		Specimen No.1	Specimen No.2	Specimen No.3	
a) Flange Length Front Edge		134.5	133.5	134	mm
b) Flange Length Side Edge		110.5	105.5	104.5	mm
c) Flange Length Left Edge		83	85.5	85	mm
d) Flange Length Rear Edge		81	85.5	83	mm
e) Peak Punch Tonnage		341	338	334	mm
f) Peak Blankholder Tonnage		82	87	84	tons
g) Corner Tonnages					
	LF	18	18	19	tons
	LR	15	16	17	tons
	RR	28	28	29	tons
	RF	26	25	24	tons

Table5

Experiment No.6					
Inputs			Setting		
a) Shut Height			62.527	in	
b) Blank Position			380	mm	
Outputs		Specimen No.1	Specimen No.2	Specimen No.3	
a) Flange Length Front Edge		122	132	129	mm
b) Flange Length Side Edge		151	149.5	139	mm
c) Flange Length Left Edge		121.5	112	100	mm
d) Flange Length Rear Edge		52	45	57.5	mm
e) Peak Punch Tonnage		334	338	338	mm
f) Peak Blankholder Tonnage		198	202	197	tons
g) Corner Tonnages					
	LF	50	50	48	tons
	LR	43	43	43	tons
	RR	59	59	59	tons
	RF	55	55	53	tons

Table6

Experiment No.7					
Inputs			Setting		
a) Shut Height			62.57	in	
b) Blank Position			380	mm	
Outputs		Specimen No.1	Specimen No.2	Specimen No.3	
a) Flange Length Front Edge		136	133	133.5	mm
b) Flange Length Side Edge		119.5	118	118.5	mm
c) Flange Length Left Edge		75	75	75.5	mm
d) Flange Length Rear Edge		81.5	87.5	85.5	mm
e) Peak Punch Tonnage		339	336	333	mm
f) Peak Blankholder Tonnage		81	79	78	tons
g) Corner Tonnages					
	LF	17	17	17	tons
	LR	16	15	16	tons
	RR	28	27	28	tons
	RF	24	23	22	tons

Table7

Experiment No.8					
Inputs			Setting		
a) Shut Height			62.57	in	
b) Blank Position			404	mm	
Outputs		Specimen No.1	Specimen No.2	Specimen No.3	
a) Flange Length Front Edge		139	140.5	138	mm
b) Flange Length Side Edge		155	145.5	153.5	mm
c) Flange Length Left Edge		48	50.5	49	mm
d) Flange Length Rear Edge		69.5	75.5	80	mm
e) Peak Punch Tonnage		337	337	338	mm
f) Peak Blankholder Tonnage		80	77	83	tons
g) Corner Tonnages					
	LF	178	18	18	tons
	LR	16	15	16	tons
	RR	27	29	28	tons
	RF	23	21	24	tons

Table8

Experiment No.9					
Inputs			Setting		
a) Shut Height			62.56	in	
b) Blank Position			380	mm	
Outputs		Specimen No.1	Specimen No.2	Specimen No.3	
a) Flange Length Front Edge		133	134	132.5	mm
b) Flange Length Side Edge		129	124	125	mm
c) Flange Length Left Edge		74	77	76.5	mm
d) Flange Length Rear Edge		75.5	75	75.5	mm
e) Peak Punch Tonnage		336	336	331	mm
f) Peak Blankholder Tonnage		110	105	101	tons
g) Corner Tonnages					
	LF	22	21	23	tons
	LR	21	21	21	tons
	RR	34	35	34	tons
	RF	33	29	29	tons

Table9

APPENDIX5

Influence of factors on Flange Length to Side Edge								
							Columns (c)	
						Shut Height		
						c1	c2	c3
						62.527	62.56	62.57
				Blank Position		125	114.5	110.5
				# 1		131	113.5	105.5
				B1		130	112.5	104.5
		Rows (r)		Blank Position		151	129	119.5
				# 2		149.5	124	118
				B2		139	125	118.5
				Blank Position		170	160	155
				# 3		175	158	145.5
				B3		172	162	153.5
					T(c)	1342.5	1198.5	1130.5
c	n	r	N	T				
3	3	3	27	3671.5				
SS(c)	SS(r)	SS (cr)	SS(total	SS(residual)				
2603.9	9489.8	64.259	12375	216.83				
				MSR min for significance				
SS	DF	MS	MSR	90%	95%	97.50%		
2603.9	2	1301.9	108.08	2.52	3.37	4.27	Shut Height	
9489.8	2	4744.9	393.89	2.52	3.37	4.27	Blank Position	
64.259	4	16.065	1.3336	2.17	2.74	3.33	Sh & Bp	
216.83	18	12.046						
12375	26							

Table1

Influence of factors on Flange Length to Front Edge								
							Columns (c)	
						Shut Height		
						c1	c2	c3
						62.527	62.56	62.57
				Blank Position		131	134	134.5
				# 1		129	133	133.5
				B1		127.5	1344	134
		Rows (r)		Blank Position		122	133	136
				# 2		132	134	133
				B2		129	132.5	133.5
				Blank Position		130	136	139
				# 3		138	136	140.5
				B3		132.5	137	138
					T(c)	1171	1209.5	1222
c	n	r	N	T				
3	3	3	27	3602.5				
SS(c)	SS(r)	SS (cr)	SS(total	SS(residual)				
157.02	115.8	8.3704	384.85	103.67				
				MSR min for significance				
SS	DF	MS	MSR	90%	95%	97.50%		
157.02	2	78.509	13.632	2.52	3.37	4.27	Shut Height	
115.8	2	57.898	10.053	2.52	3.37	4.27	Blank Position	
8.3704	4	2.0926	0.3633	2.17	2.74	3.33	Sh & Bp	
103.67	18	5.7593						
384.85	26							

Table2

Influence of factors on Flange Length to Left Edge								
							Columns (c)	
						Shut Height		
						c1	c2	c3
						62.527	62.56	62.57
				Blank Position		107	84.5	83
				# 1		95	83.5	85.5
				B1		95	85	85
		Rows (r)		Blank Position		121.5	74	75
				# 2		112	77	75
				B2		100	76.5	75.5
				Blank Position		75	50.5	48
				# 3		63	48	50.5
				B3		68	45	49
					T(c)	836.5	624	626.5
c	n	r	N	T				
3	3	3	27	2087				
SS(c)	SS(r)	SS (cr)	SS(total	SS(residual)				
3306	6594.1	480.31	10810	429.17				
				MSR min for significance				
SS	DF	MS	MSR	90%	95%	97.50%		
3306	2	1653	69.33	2.52	3.37	4.27	Shut Height	
6594.1	2	3297.1	138.28	2.52	3.37	4.27	Blank Position	
480.31	4	120.08	5.0363	2.17	2.74	3.33	Sh & Bp	
429.17	18	23.843						
10810	26							

Table3

Influence of factors on Flange Length to Rear Edge								
							Columns (c)	
						Shut Height		
						c1	c2	c3
						62.527	62.56	62.57
				Blank Position		59.5	75	81
				# 1		62.5	77.5	85.5
				B1		65.5	78	83
		Rows (r)		Blank Position		52	75.5	81.5
				# 2		45	75	87.5
				B2		57.5	75.5	85.5
				Blank Position		57.5	71.5	69.5
				# 3		54.5	73	75.5
				B3		58	74.5	80
					T(c)	512	675.5	729
c	n	r	N	T				
3	3	3	27	1916.5				
SS(c)	SS(r)	SS (cr)	SS(total	SS(residual)				
2840.1	161.46	208.81	3408.2	197.83				
				MSR min for significance				
SS	DF	MS	MSR	90%	95%	97.50%		
2840.1	2	1420.1	129.21	2.52	3.37	4.27	Shut Height	
161.46	2	80.732	7.3454	2.52	3.37	4.27	Blank Position	
208.81	4	52.204	4.7498	2.17	2.74	3.33	Sh & Bp	
197.83	18	10.991						
3408.2	26							

Table4

Influence of factors on Peak Punch Tonnage								
							Columns (c)	
						Shut Height		
						c1	c2	c3
						62.527	62.56	62.57
				Blank Position		326	334	341
				# 1		328	333	338
				B1		334	331	334
		Rows (r)		Blank Position		334	336	339
				# 2		338	336	336
				B2		338	331	333
				Blank Position		334	330	337
				# 3		337	339	337
				B3		336	333	338
					T(c)	3005	3003	3033
c	n	r	N	T				
3	3	3	27	9041				
SS(c)	SS(r)	SS (cr)	SS(total	SS(residual)				
62.519	35.852	68.37	323.41	156.67				
				MSR min for significance				
SS	DF	MS	MSR	90%	95%	97.50%		
62.519	2	31.259	3.5915	2.52	3.37	4.27	Shut Height	
35.852	2	17.926	2.0596	2.52	3.37	4.27	Blank Position	
68.37	4	17.093	1.9638	2.17	2.74	3.33	Sh & Bp	
156.67	18	8.7037						
323.41	26							

Table5

Influence of factors on Peak Blankholder Tonnage								
							Columns (c)	
						Shut Height		
						c1	c2	c3
						62.527	62.56	62.57
				Blank Position		205	107	82
				# 1		204	106	87
				B1		208	98	84
		Rows (r)		Blank Position		198	110	81
				# 2		202	105	79
				B2		197	101	78
				Blank Position		202	110	80
				# 3		200	103	77
				B3		198	107	83
					T(c)	1814	947	731
c	n	r	N	T				
3	3	3	27	3492				
SS(c)	SS(r)	SS (cr)	SS(total	SS(residual)				
73009	52.667	82.667	73324	180				
				MSR min for significance				
SS	DF	MS	MSR	90%	95%	97.50%		
73009	2	36504	3650.4	2.52	3.37	4.27	Shut Height	
52.667	2	26.333	2.6333	2.52	3.37	4.27	Blank Position	
82.667	4	20.667	2.0667	2.17	2.74	3.33	Sh & Bp	
180	18	10						
73324	26							

Table6

Influence of factors on Left Front Blankholder Tonnage								
							Columns (c)	
						Shut Height		
						c1	c2	c3
						62.527	62.56	62.57
				Blank Position		50	24	18
				# 1		49	24	18
				B1		52	22	19
		Rows (r)		Blank Position		50	22	17
				# 2		50	21	17
				B2		48	23	17
				Blank Position		51	23	17
				# 3		49	26	18
				B3		50	23	18
					T(c)	449	208	159
c	n	r	N	T				
3	3	3	27	816				
SS(c)	SS(r)	SS (cr)	SS(total	SS(residual)				
5354.9	8.2222	2.2222	5386.7	21.333				
				MSR min for significance				
SS	DF	MS	MSR	90%	95%	97.50%		
5354.9	2	2677.4	2259.1	2.52	3.37	4.27	Shut Height	
8.2222	2	4.1111	3.4688	2.52	3.37	4.27	Blank Position	
2.2222	4	0.5556	0.4688	2.17	2.74	3.33	Sh & Bp	
21.333	18	1.1852						
5386.7	26							

Table7

Influence of factors on Left Rear Blankholder Tonnage								
							Columns (c)	
						Shut Height		
						c1	c2	c3
						62.527	62.56	62.57
				Blank Position		44	20	15
				# 1		44	20	16
				B1		45	20	17
		Rows (r)		Blank Position		43	21	16
				# 2		43	21	15
				B2		43	21	16
				Blank Position		43	22	16
				# 3		43	20	15
				B3		43	22	16
					T(c)	392	187	142
c	n	r	N	T				
3	3	3	27	721				
SS(c)	SS(r)	SS (cr)	SS(total	SS(residual)				
3946.3	0.2963	5.7037	3959.6	7.3333				
				MSR min for significance				
SS	DF	MS	MSR	90%	95%	97.50%		
3946.3	2	1973.1	4843.2	2.52	3.37	4.27	Shut Height	
0.2963	2	0.1481	0.3636	2.52	3.37	4.27	Blank Position	
5.7037	4	1.4259	3.5	2.17	2.74	3.33	Sh & Bp	
7.3333	18	0.4074						
3959.6	26							

Table8

Influence of factors on Right Rear Blankholder Tonnage								
							Columns (c)	
						Shut Height		
						c1	c2	c3
						62.527	62.56	62.57
				Blank Position		59	33	28
				# 1		57	34	28
				B1		59	32	29
		Rows (r)		Blank Position		59	34	28
				# 2		59	35	27
				B2		59	34	28
				Blank Position		59	34	27
				# 3		58	34	29
				B3		55	33	28
					T(c)	524	303	252
c	n	r	N	T				
3	3	3	27	1079				
SS(c)	SS(r)	SS (cr)	SS(total)	SS(residual)				
4645.4	2.0741	5.4815	4671	18				
				MSR min for significance				
SS	DF	MS	MSR	90%	95%	97.50%		
4645.4	2	2322.7	2322.7	2.52	3.37	4.27	Shut Height	
2.0741	2	1.037	1.037	2.52	3.37	4.27	Blank Position	
5.4815	4	1.3704	1.3704	2.17	2.74	3.33	Sh & Bp	
18	18	1						
4671	26							

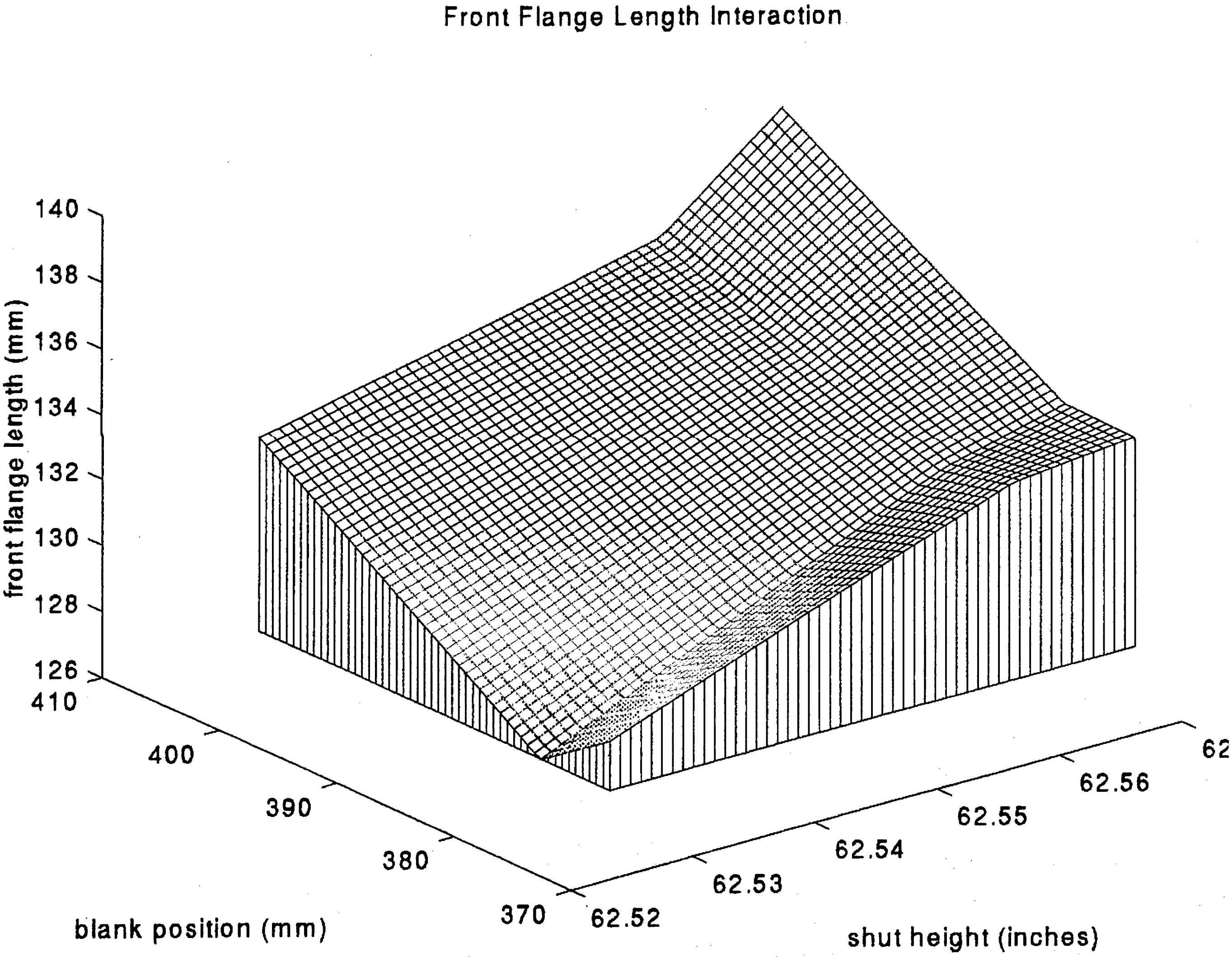
Table9

Influence of factors on Right Front Blankholder Tonnage								
							Columns (c)	
						Shut Height		
						c1	c2	c3
						62.527	62.56	62.57
				Blank Position		55	32	26
				# 1		56	30	25
				B1		56	26	24
		Rows (r)		Blank Position		55	33	24
				# 2		55	29	23
				B2		53	29	22
				Blank Position		56	31	23
				# 3		53	28	21
				B3		53	30	24
					T(c)	492	268	212
c	n	r	N	T				
3	3	3	27	972				
SS(c)	SS(r)	SS (cr)	SS(total	SS(residual)				
4878.2	6.8889	8.8889	4946	52				
				MSR min for significance				
SS	DF	MS	MSR	90%	95%	97.50%		
4878.2	2	2439.1	844.31	2.52	3.37	4.27	Shut Height	
6.8889	2	3.4444	1.1923	2.52	3.37	4.27	Blank Position	
8.8889	4	2.2222	0.7692	2.17	2.74	3.33	Sh & Bp	
52	18	2.8889						
4946	26							

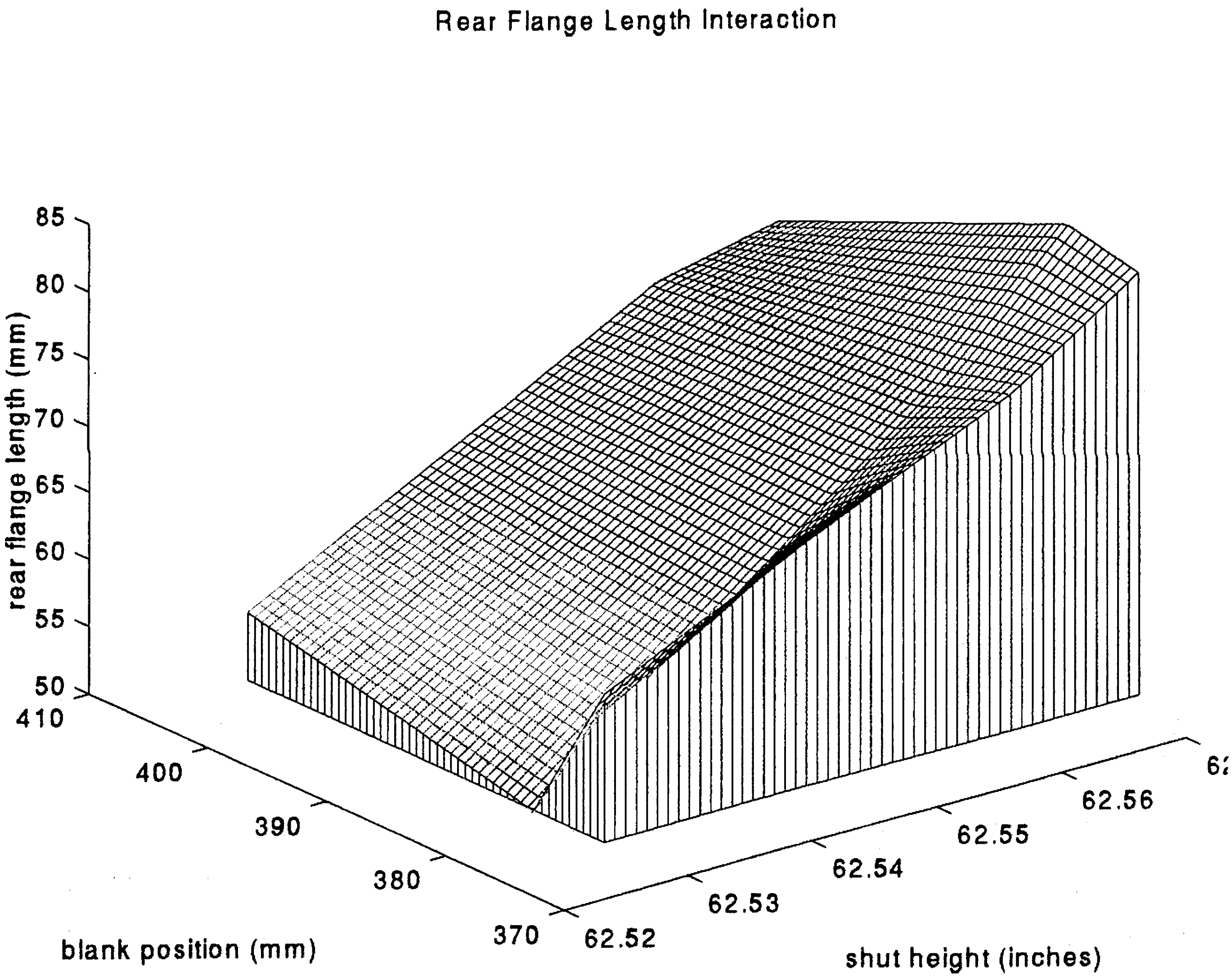
Table10

APPENDIX6

Graph No.1

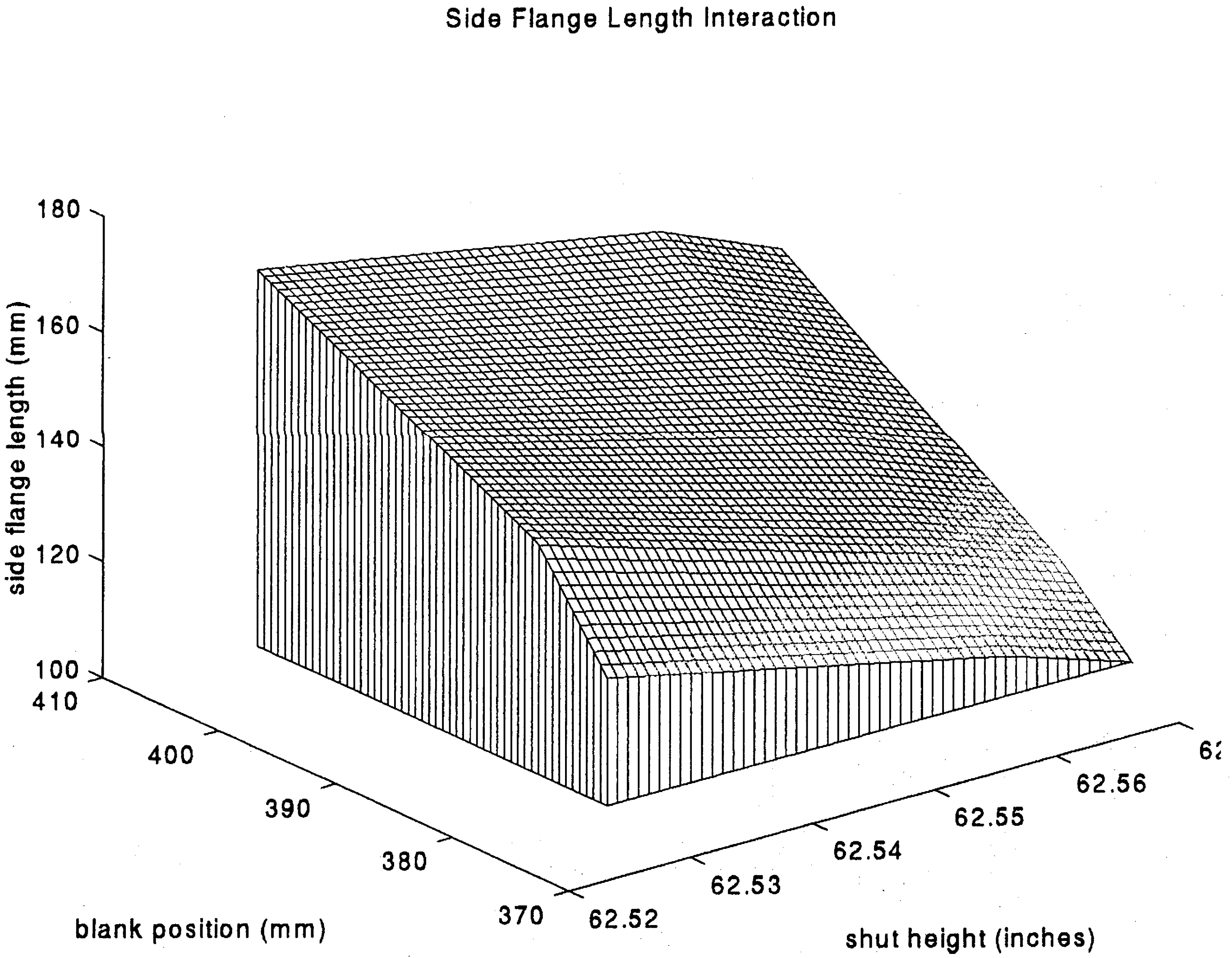

Front Flange Length Interaction
front flange length (mm)
140
138
136
134
132
130
128
126
410
400
390
380
370
blank position (mm)
62.52
62.53
62.54
62.55
62.56
62
shut height (inches)

Graph No.2



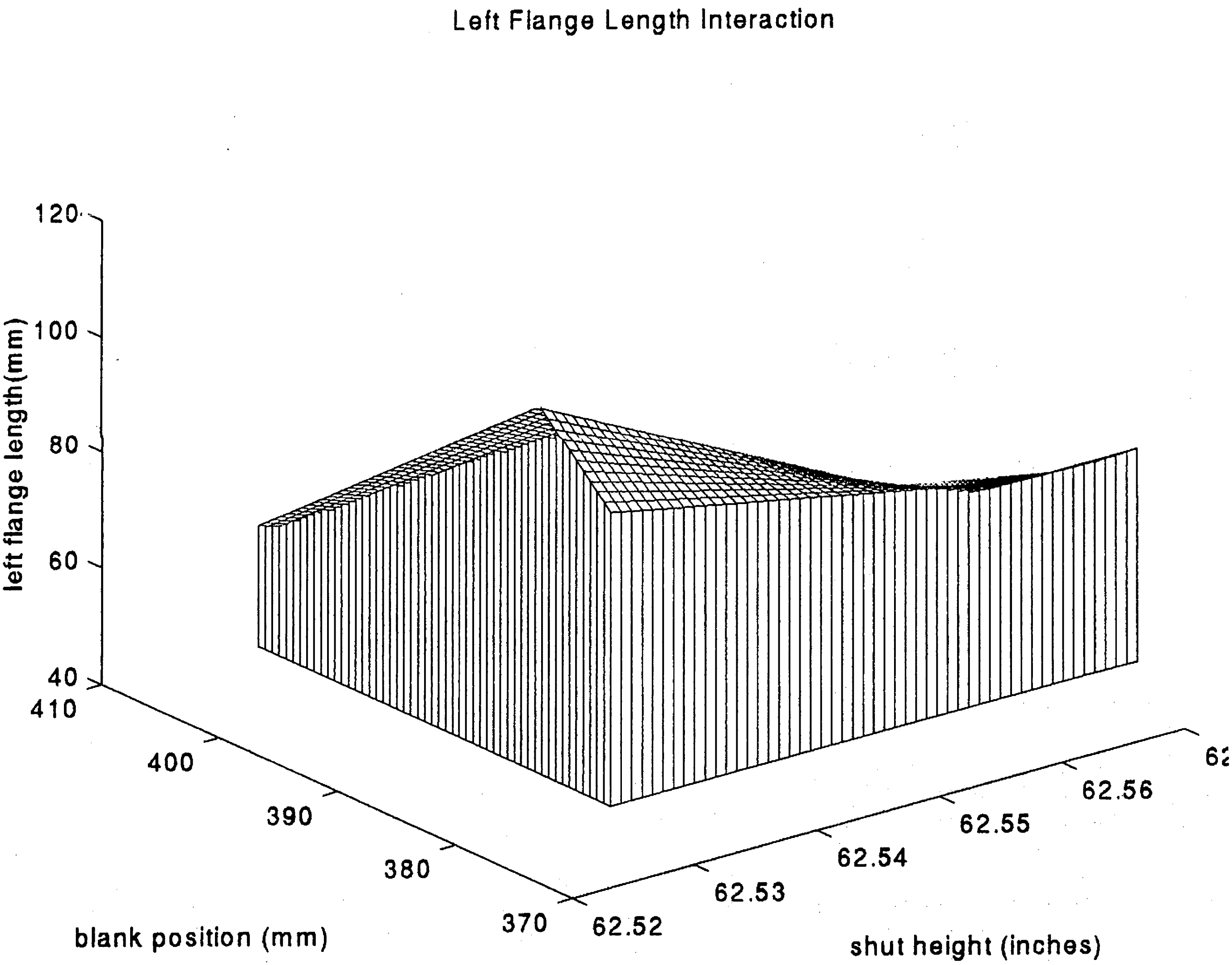
Rear Flange Length Interaction
rear flange length (mm)
85
80
75
70
65
60
55
50
410
400
390
380
370
blank position (mm)
62.52
62.53
62.54
62.55
62.56
shut height (inches)

Graph No.3



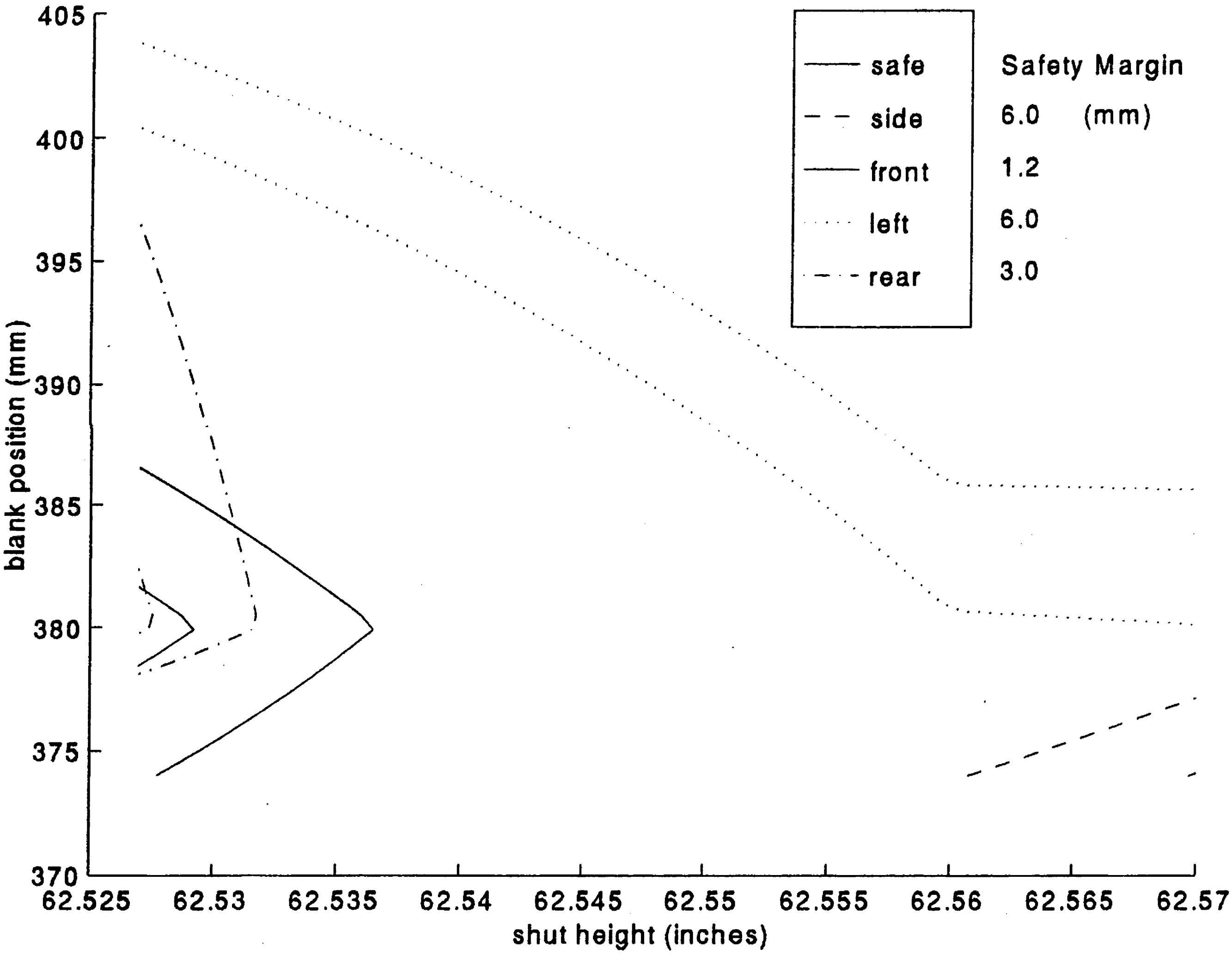
Side Flange Length Interaction
side flange length (mm)
180
160
140
120
100
410
400
390
380
370
blank position (mm)
62.52
62.53
62.54
62.55
62.56
shut height (inches)

Graph No.4



Left Flange Length Interaction
left flange length(mm)
120
100
80
60
40
410
400
390
380
370
blank position (mm)
62.52
62.53
62.54
62.55
62.56
shut height (inches)

Graph No.5



405
400
395
390
385
380
375
370
blank position (mm)
62.525
62.53
62.535
62.54
62.545
62.55
62.555
62.56
62.565
62.57
shut height (inches)
safe
side
front
left
rear
Safety Margin
6.0 (mm)
1.2
6.0
3.0

APPENDIX7

Location of Measurement	Minimum amount of Draw-in (mm)
Side Edge	107
Front Edge	127
Left Edge	68
Rear Edge	57

APPENDIX8

Corner Pressure - Analysis of Factorial Design

Front Edge

Expt No.	A	B	C	D	AB	AC	BC	AD	BD	CD	ABC	ABD	ACD	BCD	ABCD	Frnt Edge	Variance	% of Value
1	-	-	-	-	+	+	+	+	+	+	-	-	-	-	+	134.8	7.056667	5.234916
9	+	-	-	-	-	-	+	+	+	+	+	+	+	-	-	135.7	9.39	6.919676
5	-	+	-	-	-	+	-	+	-	+	+	+	-	+	-	134.7	2.056667	1.52685
13	+	+	-	-	+	-	-	-	-	+	-	-	+	+	+	136.7	1.056667	0.772982
3	-	-	+	-	+	-	-	+	+	-	+	-	+	+	+	135.2	3.39	2.507396
11	+	-	+	-	-	+	-	-	+	-	-	+	-	+	+	132	12.66667	9.59596
7	-	+	+	-	-	-	+	+	-	-	-	+	+	-	+	133.3	7.39	5.543886
15	+	+	+	-	+	+	+	-	-	-	+	-	-	-	-	135.5	14	10.3321
2	-	-	-	+	+	+	+	-	-	-	-	+	+	+	-	133.5	6.166667	4.619226
10	+	-	-	+	-	-	+	+	-	-	+	-	-	+	+	135.2	4.223333	3.123767
6	-	+	-	+	-	+	-	-	+	-	+	-	+	-	+	135.3	3.39	2.505543
14	+	+	-	+	+	-	-	+	+	-	-	+	-	-	-	136.7	1.39	1.016825
4	-	-	+	+	-	-	-	-	-	+	+	+	-	-	+	136.3	3.723333	2.731719
12	+	-	+	+	-	+	-	+	-	+	-	-	+	-	-	134.2	6.056667	4.513164
8	-	+	+	+	-	-	+	-	+	+	-	-	-	+	-	136.8	17.05667	12.46832
16	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	136	8.166667	6.004902
Frnt Edge																		
=sum+	1082	1085	1079.3	1077.9	948.4	1076	1080.8	1215.8	1082.5	1085.2	1083.9	1078.2	1079.9	1080.1	1214.8		Ave % of	4.963577
=sum -	1079.9	1076.9	1082.6	1084	1213.5	1085.9	1081.1	946.1	1079.4	1076.7	1078	1083.7	1082	1081.8	947.1		Value	
=diffence	2.1	8.1	-3.3	-6.1	-265.1	-9.9	-0.3	269.7	3.1	8.5	5.9	-5.5	-2.1	-1.7	267.7			

Side Edge

Expt No.	A	B	C	D	AB	AC	BC	AD	BD	CD	ABC	ABD	ACD	BCD	ABCD	Sde Edge	Variance	% of Value
1	-	-	-	-	+	+	+	+	+	+	-	-	-	-	+	106.5	16.66667	15.64945
9	+	-	-	-	-	-	+	+	+	+	+	+	+	-	-	112.2	7.406667	6.601307
5	-	+	-	-	-	+	-	+	-	+	+	+	-	+	-	119.5	18.16667	15.20223
13	+	+	-	-	+	-	-	-	-	+	-	-	+	+	+	104.8	8.723333	8.323791
3	-	-	+	-	+	-	-	+	+	-	+	-	+	+	+	111.7	2.39	2.13966
11	+	-	+	-	-	+	-	-	+	-	-	+	-	+	+	115.8	7.39	6.381693
7	-	+	+	-	-	-	+	+	-	-	-	+	+	-	+	116.2	5.073333	4.366036
15	+	+	+	-	+	+	+	-	-	-	+	-	-	-	-	110.8	6.223333	5.616727
2	-	-	-	+	+	+	+	-	-	-	-	+	+	+	-	111.2	8.39	7.544964
10	+	-	-	+	-	-	+	+	-	-	+	-	-	+	+	107	15.5	14.48598
6	-	+	-	+	-	+	-	-	+	-	+	-	+	-	+	106	24.25	22.87736
14	+	+	-	+	+	-	-	+	+	-	-	+	-	-	-	103.7	16.24	15.66056
4	-	-	+	+	-	-	-	-	-	+	+	+	-	-	+	113.7	4.223333	3.714453
12	+	-	+	+	-	+	-	+	-	+	-	-	+	-	-	110.7	33.55667	30.31316
8	-	+	+	+	-	-	+	-	+	+	-	-	-	+	-	101.3	8.39	8.28233
16	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	106.5	14	13.14554
Side Edge																		
=sum+	871.5	868.8	886.7	897.5	755.2	887	871.7	994	863.7	875.2	887.4	898.8	879.3	877.8	988.2		Ave % of	11.26908
=sum -	886.1	888.8	870.9	860.1	1002.4	870.6	885.9	763.6	893.9	882.4	870.2	858.8	878.3	879.8	769.4		Value	
=diffence	-14.6	-20	15.8	37.4	-247.2	16.4	-14.2	230.4	-30.2	-7.2	17.2	40	1	-2	218.8			

Expt No.	A	B	C	D	AB	AC	BC	AD	BD	CD	ABC	ABD	ACD	BCD	ABCD	Lft Edge	Variance	% of Value
1	-	-	-	-	+	+	+	+	+	+	-	-	-	-	+	93.8	2.056667	2.192608
9	+	-	-	-	-	-	+	+	+	+	+	+	+	-	-	90.5	18.16667	20.07366
5	-	+	-	-	-	+	-	+	-	+	+	+	-	+	-	86.5	15.16667	17.53372
13	+	+	-	-	+	-	-	-	-	+	-	-	+	+	+	98.8	36.20667	36.64642
3	-	-	+	-	+	-	-	+	+	-	+	-	+	+	+	88	0.666667	0.757576
11	+	-	+	-	-	+	-	-	+	-	-	+	-	+	+	84.5	0.5	0.591716
7	-	+	+	-	-	-	+	+	-	-	-	+	+	-	+	87	14.39	16.54023
15	+	+	+	-	+	+	+	-	-	-	+	-	-	-	-	87.3	0.723333	0.828561
2	-	-	-	+	+	+	+	-	-	-	-	+	+	+	-	87.5	0.166667	0.190476
10	+	-	-	+	-	-	+	+	-	-	+	-	-	+	+	93.8	32.89	35.06397
6	-	+	-	+	-	+	-	-	+	-	+	-	+	-	+	97.8	10.05667	10.28289
14	+	+	-	+	+	-	-	+	+	-	-	+	-	-	-	99.2	18.72333	18.87433
4	-	-	+	+	-	-	-	-	-	+	+	+	-	-	+	87.3	5.056667	5.792287
12	+	-	+	+	-	+	-	+	-	+	-	-	+	-	-	89.7	14.39	16.04236
8	-	+	+	+	-	-	+	-	+	+	-	-	-	+	-	99.2	16.22333	16.35417
16	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	88.8	8.723333	9.823574
Left Edge																		
=sum+	732.6	744.6	711.8	716.4	643.4	715.9	727.9	817.3	741.8	734.6	720	711.3	728.1	727.1	819.8		Ave % of	12.97428
=sum -	727.1	715.1	747.9	743.3	816.3	743.8	731.8	642.4	717.9	725.1	739.7	748.4	731.6	732.6	639.9		Value	
=diffence	5.5	29.5	-36.1	-26.9	-172.9	-27.9	-3.9	174.9	23.9	9.5	-19.7	-37.1	-3.5	-5.5	179.9			

Rear Edge

Expt No.	A	B	C	D	AB	AC	BC	AD	BD	CD	ABC	ABD	ACD	BCD	ABCD	Rr Edge	Variance	% of Value
1	-	-	-	-	+	+	+	+	+	+	-	-	-	-	+	63.5	8.166667	12.86089
9	+	-	-	-	-	-	+	+	+	+	+	+	+	-	-	61	1.166667	1.912568
5	-	+	-	-	-	+	-	+	-	+	+	+	-	+	-	62.7	2.723333	4.343434
13	+	+	-	-	+	-	-	-	-	+	-	-	+	+	+	61.7	1.39	2.252836
3	-	-	+	-	+	-	-	+	+	-	+	-	+	+	+	63.5	0.666667	1.049869
11	+	-	+	-	-	+	-	-	+	-	-	+	-	+	+	65.5	8.166667	12.46819
7	-	+	+	-	-	-	+	+	-	-	-	+	+	-	+	62.3	8.723333	14.00214
15	+	+	+	-	+	+	+	-	-	-	+	-	-	-	-	61.3	3.556667	5.802066
2	-	-	-	+	+	+	+	-	-	-	-	+	+	+	-	63	8.666667	13.75661
10	+	-	-	+	-	-	+	+	-	-	+	-	-	+	+	62	0.5	0.806452
6	-	+	-	+	-	+	-	-	+	-	+	-	+	-	+	59.3	0.89	1.500843
14	+	+	-	+	+	-	-	+	+	-	-	+	-	-	-	58.5	15.16667	25.92593
4	-	-	+	+	-	-	-	-	-	+	+	+	-	-	+	59.7	0.223333	0.374093
12	+	-	+	+	-	+	-	+	-	+	-	-	+	-	-	62.5	8.166667	13.06667
8	-	+	+	+	-	-	+	-	+	+	-	-	-	+	-	57.7	5.723333	9.919122
16	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	64.5	3.166667	4.909561
Rear Edge																		
=sum+	497	488	497	501.5	436	502.3	495.3	560.5	493.5	493.3	494	497.2	497.8	500.6	562		Ave % of	7.809455
=sum -	491.7	500.7	491.7	487.2	552.7	486.4	493.4	428.2	495.2	495.4	494.7	491.5	490.9	488.1	426.7		Value	
=diffence	5.3	-12.7	5.3	14.3	-116.7	15.9	1.9	132.3	-1.7	-2.1	-0.7	5.7	6.9	12.5	135.3			

DEFINITIONS

Bodyside -	Structural component of car chasis. Includes a, b and c pillar and in some cases a quarter panel.
Skin finish -	Car panel which comprises part of the outside shell. These are the panels that the eye sees. They must be of extremely high surface finish in order to maximise outside appearance.
P.C.P -	Stands for Process Control Plan. Is a document used for each process listing what the appropriate press settings and material press settings are for each job.
Hit-to-Hit -	Is a term used to describe a period of time. The hit-to-hit time is the amount of time elapsed between the time a job finished to the time the same job is running again satisfactorily. Much time is spent in the setup of a job. Improvements is setup time will be reflected in the hit-to-hit time.

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